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Feasibility Study for Adapting Present Combustion Source Continuous Monitoring Systems to Hazardous Waste Incinerators Volume 2. Review and Estimation of Incineration Test Conditions

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FEASIBILITY STUDY FOR ADAPTING PRESENT COMBUSTION SOURCE CONTINUOUS MONITORING SYSTEMS TO HAZARDOUS WASTE INCINERATORS

Volume 2. Review and Estimation of Incineration Test Conditions

by

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16. ABSTRACT The report gives results of an adaptability study of commercially available sample conditioning and measurement systems, in the form of a guidelines document to be used by EPA and industry personnel. As part of EPA-sponsored research programs to investigate sampling and analysis methods for hazardous waste incineration (focused on adapting existing methods for identifying and quantifying constituents listed in 40 CFR 261), the adaptability of existing continuous emission monitoring systems (CEMS) involves such measurement categories as SO2, SO3, NOx, CO, CO2, O2, HCl, and organic materials. Study results indicate that commercially available extractive continuous monitors can be adapted to incinerators through proper sample conditioning. Available CEMS provide the ranges and sensitivities needed to accurately measure concentrations of the organic and inorganic components of interest.

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Incinerators		Continuous Monitors	
Wastes		Hazardous Waste	
Toxicity		Sample Conditioning	06T
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ABSTRACT

The U.S. Environmental Protection Agency is sponsoring research programs to investigate sampling and analysis methods for hazardous waste incineration. These investigations are focused upon the adaptation of existing methods for identifying and quantifying those constituents listed in 40 CFR 261 of the regulations. As part of this program, the adaptability of existing continuous emission monitors systems (CEMS) to hazardous waste incineration sources was investigated. Measurement categories of interest include SO_2, SO_3, NO_x, CO, CO_2, O_2, HCl, and organic materials. This report focuses on commercially available sample conditioning and measurement systems, and presents the results of this adaptability study in the form of a guidelines document to be used by agency and industry personnel.

The results of this study indicate that commercially available extractive continuous monitors can be adapted to incinerators through proper sample conditioning. Conventional sample conditioning systems that dry and remove particulate matter from the sample gas should be constructed to withstand HCl gas concentrations of up to 17 percent v/v and temperatures reaching 1700°C (3000°F). Presently available continuous monitoring instrumentation provides the ranges and sensitivities needed to accurately measure concentrations of the organic and inorganic components of interest.

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SECTION 1

INTRODUCTION

Proper disposal of hazardous wastes is one of the key environmental problems of this decade. The environmental abuse associated with improperly managed, hazardous waste disposal areas, such as the Love Canal site near Niagara Falls, has alerted all citizens of the need for closely regulated disposal facilities. To this end the United States Congress in 1976 passed Federal Law 94-580, the Resource Conservation and Recovery Act (RCRA). Regulations promulgated under the authority of this legislation establishes the framework for a strong federal hazardous waste management program.[1] These regulations define those wastes that are hazardous and set standards for waste generators, transporters and hazardous waste management facilities. In addition, the hazardous waste regulations set forth applicable physical, chemical, biological and thermal processes that can be used to treat hazardous wastes.

Disposal of hazardous wastes is limited to four options: ocean dumping, deep well injection, landfilling and incineration. These processes were used to dispose of the estimated 57 million metric tons of hazardous wastes that were generated by industry in 1980.[2] The choice of which method is used depends on several factors including the amount of waste to be handled, its composition and heat content, the availability of suitable local disposal sites and the overall disposal economics.

Incineration is beginning to emerge as an especially attractive disposal technology for several reasons. These include:[2]

- Toxic components of hazardous wastes can be converted to harmless compounds or, at least, to less harmful compounds.
- Incineration provides for the ultimate disposal of hazardous wastes eliminating the possibility of problems resurfacing in the future.
- The volume of hazardous waste is greatly reduced by incineration.
- Heat recovery makes it possible to recover some of the energy produced by the combustion process.

The U.S. Environmental Protection Agency estimates that in 1979 only 5 percent of the total hazardous waste stream in the United States were incinerated, yet 60 percent of the total wastes could have been destroyed using current incinerator technology.[2]

The performance of an incinerator used for hazardous waste disposal can, in part, be monitored and defined by Continuous Emission Monitors (CEMS). By continuously measuring and recording flue gas parameters such as carbon dioxide (CO_2), carbon monoxide (CO), and hydrocarbon (HC) concentrations, and temperature and moisture (H_2O) levels, the thermal and combustion efficiency of the incinerator can be determined. In addition, CEMS can continuously measure specific pollutant emission rates which will determine the operating efficiency of installed Air Pollution Control (APC) devices as well as the compliance status of the incinerator with respect to Federal, state and local pollutant emission regulations.

The environment in which a hazardous waste CEM operates is unlike that existent of other combustion systems. The wide variation in the composition of materials which are classified as hazardous, the unlimited number of combinations in which these materials may be mixed and burned and the varying combustion characteristics of the individual wastes result in an incinerator environment that can change substantially from site to site and from burn to burn.

This report attempts to define the environment of a hazardous waste incinerator, specifically that range of conditions in which a CEM must operate. This environment will be defined by the combustion gas temperature, pressure, excess air and moisture levels, as well as the concentrations of four primary atmospheric pollutants; hydrogen chloride (HCl), carbon monoxide (CO), sulfur dioxide (SO_2) and nitrogen oxides (NO_x). In addition the concentrations of two important combustion process indicators, carbon dioxide and oxygen will also be addressed.

Operating conditions will be defined and discussed for three principal sites within a hazardous waste incineration system; in the combustion chamber where a CEM may be used in determining combustion efficiency, prior to the APC device where a CEM can assist in determining control device efficiency and after the APC device, where the quantification of pollutant control efficiency in addition to establishing atmospheric discharge rates from the incinerator is essential.

The operating conditions will be defined for these three monitoring zones for three principal types of incinerators currently in use for hazardous waste incineration; liquid injection, rotary kiln and fluidized bed. By defining operating conditions in a number of incinerators, as well as a number of monitoring locations, more potential CEM installation sites will be described and the various conditions to be expected will be more clearly understood.

Perhaps the greatest variable in determining flue gas conditions within a hazardous waste incinerator is the waste itself. To adequately understand the extent of this variation, this report will first describe hazardous wastes, the ranges in elemental composition which are encompassed and the combustion byproducts that result when pure compounds or a mixture of wastes is burned. The three types of incinerators will then be described, to present the major differences and the relative advantages and disadvantages of each. This will

be followed by a brief description of the common air pollution control devices which may be installed, singularly or in tandem, to limit pollutant emissions to the atmosphere. These capsule summaries will further clarify the operating conditions that exist after the control device. The actual operating conditions at the three potential monitoring locations will then be described.

Any description of hazardous waste incineration must be prefaced with a statement on the wide range of descriptions for a "typical" hazardous waste facility. There is no such operation. Hazardous waste, unlike municipal waste or sewage sludge is not a uniform, homogeneous product, for which "ideal" incineration conditions can be set and expected operating parameters narrowly estimated. In fact the exact incineration characteristics of each of the hazardous wastes defined by RCRA has yet to be firmly established.[3] It goes without saying that the incineration requirements for a small industrial concern producing one or two specific hazardous wastes will be drastically different from the large commercial incineration facility that accepts virtually any type of waste. The wastes will be different and the flue gas environment will be different. Rather than attempt to describe all possible combinations of wastes/incinerators/flue gas compositions, this report will present the variations in each specific category. It is left to the reader to understand that each installation must be handled individually, and that the range of conditions defined at each monitoring location may not always apply in each situation.

SECTION 2

HAZARDOUS WASTES

In order to implement Subtitle C of the Resource Conservation and Recovery Act (RCRA), the Environmental Protection Agency (EPA) has promulgated a broad range of regulations concerning the management of hazardous waste materials (40 CFR 260-267).[1] Hazardous wastes are defined by these regulations (40 CFR Part 261, Subpart C) according to the ignitability, corrosivity, reactivity, and EP toxicity of the waste stream. Each of these four waste characteristics is more specifically defined in Subpart C and reference is made to Subpart D of the regulations which lists actual wastes and waste streams that are considered hazardous. An integral section of Subpart D is Appendix VIII which lists toxic constituents. The presence of any of these constituents in a waste stream defines that stream as hazardous (§261.11). Since the Appendix VIII list of hazardous constituents is not specific to any industry, it has greater broad based applicability than the other waste-stream definitions and was therefore selected as the basis for reviewing the composition and potential flue gas emissions of hazardous waste materials. This Appendix VIII list is presented in Table 1.

There are 375 separate compounds listed as hazardous constituents in Appendix VIII. These compounds range from pure metallic elements such as beryllium, cadmium, chromium and lead, to complex compounds containing up to six different elements such as cyclophosphamide ($C_7H_{15}Cl_2N_2O_2P$) and dimethoate ($C_5H_{12}NO_3PS_2$). The physical states of the Appendix VIII compounds, their ability to be incinerated and the combustion products they generate when exposed to the hot oxidizing environment in an incinerator vary substantially. The combustion characteristics of chemically complex compounds are especially difficult to quantify since, upon incineration, they may in part break down into a number of other complex substances, depending on the specific combustion zone atmosphere. While much work has been done on defining the combustion characteristics of Appendix VIII wastes, there is still much more to do. For example, only 18 percent of these wastes have a defined auto ignition temperature,[3] a parameter useful in determining a compound's ability to be incinerated. This study will not attempt to define the limits of current research in this area. The Appendix VIII compounds will be examined according to their elemental make-up and what reactions should occur in an incinerator if the correct combustion conditions (time, temperature and turbulence) are present and what typical incomplete combustion byproducts may be formed if an ideal oxidizing atmosphere is not present.

TABLE 1. APPENDIX VIII HAZARDOUS CONSTITUENTS

Appendix VIII

[Appendix VIII revised by 46 FR 27476, May 20, 1981; corrected by 46 FR 29708, June 3, 1981]

Hazardous Constituents

Acetonitrile (Ethanenitrile)
Acetophenone (Ethanone, 1-phenyl)
3-(alpha-Acetonylbenzyl) 4-hydroxycoumarin and salts (Warfarin)
2-Acetylaminofluorene (Acetamide, N-(9H-fluoren-2-yl)-)
Acetyl chloride (Ethanoyl chloride)
1-Acetyl-2-thiourea (Acetamide, N-(aminothioxomethyl)-)
Acrolein (2-Propenal)
Acrylamide (2-Propenamide)
Acrylonitrile (2-Propenenitrile)
Aflatoxins
Aldrin (1,2,3,4,10,10-Hexachloro-1,4,4a,5,8,8a,8b-hexahydro-endo,exo-1,4:5,8-Dimethanonaphthalene)
Allyl alcohol (2-Propen-1-ol)
Aluminum phosphide
4-Aminobiphenyl ([1,1'-Biphenyl]-4-amine)
6-Amino-1,1a,2,8,8a,8b-hexahydro-8-(hydroxymethyl)-8a-methoxy-5-methylcarbamate azirino[2',3':3,4]pyrrolo[1,2-a]indole-4,7-dione (ester) (Mitomycin C)
(Azirino[2',3':3,4]pyrrolo(1,2-a)indole-4,7-dione, 6-amino-8-[((amino-carbonyl)oxy)methyl]-1,1a,2,8,8a,8b-hexahydro-8amethoxy-5-methy-)
5-(Aminomethyl)-3-isoxazolol (3(2H)-Isoxazolone, 5-(aminomethyl)-)(4-Aminopyridine (4-Pyridinamine)
Amitrole (1H-1,2,4-Triazol-3-amine)
Aniline (Benzenamine)
Antimony and compounds, N.O.S.*
Aramite (Sulfurous acid, 2-chloroethyl- 2-[4-(1,1-dimethylethyl)phenoxy]-1-methylethyl ester)
Arsenic and compounds, N.O.S.*
Arsenic acid (Orthoarsenic acid)
Arsenic pentoxide (Arsenic (V) oxide)
Arsenic trioxide (Arsenic (III) oxide)
Auramine (Benzenamine, 4,4'-carbonimidoylbis[N,N-Dimethyl-, monohydrochloride)
Azaserine (L-Serine, diazoacetate (ester))
Barium and compounds, N.O.S.*
Barium cyanide
Benz[c]acridine (3,4-Benzacridine)
Benz[a]anthracene (1,2-Benzanthracene)
Benzene (Cyclohexatriene)
Benzenearsonic acid (Arsonic acid, phenyl-)
Benzene, dichloromethyl- (Benzal chloride)
Benzenethiol (Thiophenol)
Benzidine ([1,1'-Biphenyl]-4,4'diamine)
Benzo[b]fluoranthene (2,3-Benzofluoranthene)
Benzo[j]fluoranthene (7,8-Benzofluoranthene)
Benzo[a]pyrene (3,4-Benzopyrene)
p-Benzoquinone (1,4-Cyclohexadienedione)
Benzotrichloride (Benzene, trichloromethyl-)
Benzyl chloride (Benzene, (chloromethyl)-)
Beryllium and compounds, N.O.S.*
Bis(2-chloroethoxy)methane (Ethane, 1,1'-[methylenebis(oxy)]bis[2-chloro-])
Bis(2-chloroethyl) ether (Ethane, 1,1'-oxybis[2-chloro-])
N,N-Bis(2-chloroethyl)-2-naphthylamine (Chlornaphazine)
Bis(2-chloroisopropyl) ether (Propane, 2,2'-oxybis[2-chloro-])
Bis(chloromethyl) ether (Methane, oxybis[chloro-])
Bis(2-ethylhexyl) phthalate (1,2-Benzenedicarboxylic acid, bis(2-ethylhexyl) ester)
Bromoacetone (2-Propanone, 1-bromo-)
Bromomethane (Methyl bromide)
4-Bromophenyl phenyl ether (Benzene, 1-bromo-4-phenoxy-)
Brucine (Strychnidin-10-one, 2,3-dimethoxy-)
2-Butanone peroxide (Methyl ethyl ketone, peroxide)
Butyl benzyl phthalate (1,2-Benzenedicarboxylic acid, butyl phenylmethyl ester)
2-sec-Butyl-4,6-dinitrophenol (DNBP) (Phenol, 2,4-dinitro-6-(1-methylpropyl)-)
Cadmium and compounds, N.O.S.*
Calcium chromate (Chromic acid, calcium salt)
Calcium cyanide
Carbon disulfide (Carbon bisulfide)
Carbon oxyfluoride (Carbonyl fluoride)
Chloral (Acetaldehyde, trichloro-)
Chlorambucil (Butanoic acid, 4-[bis(2-chloroethyl)amino]benzene-)
Chlordane (alpha and gamma isomers) (4,7-Methanoindan, 1,2,4,5,6,7,8,8-octachloro-3,4,7,7a-tetrahydro-) (alpha and gamma isomers)
Chlorinated benzenes, N.O.S.*
Chlorinated ethane, N.O.S.*
Chlorinated fluorocarbons, N.O.S.*
Chlorinated naphthalene, N.O.S.*
Chlorinated phenol, N.O.S.*
Chloroacetaldehyde (Acetaldehyde, chloro-)
Chloroalkyl ethers, N.O.S.*
p-Chloroaniline (Benzenamine, 4-chloro-)
Chlorobenzene (Benzene, chloro-)
Chlorobenzilate (Benzeneacetic acid, 4-chloro-alpha-(4-chlorophenyl)-alpha-hydroxy-, ethyl ester)
p-Chloro-m-cresol (Phenol, 4-chloro-3-methyl)
1-Chloro-2,3-epoxypropane (Oxirane, 2-(chloromethyl)-)
2-Chloroethyl vinyl ether (Ethene, (2-chloroethoxy)-)
Chloroform (Methane, trichloro-)
Chloromethane (Methyl chloride)
Chloromethyl methyl ether (Methane, chloromethoxy-)
2-Chloronaphthalene (Naphthalene, beta-chloro-)
2-Chlorophenol (Phenol, o-chloro-)
1-(o-Chlorophenyl)thiourea (Thiourea, (2-chlorophenyl)-)
3-Chloropropionitrile (Propanenitrile, 3-chloro-)
Chromium and compounds, N.O.S.*
Chrysene (1,2-Benzphenanthrene)
Citrus red No. 2 (2-Naphthol, 1-[(2,5-dimethoxyphenyl)azo]-)
Coal tars
Copper cyanide
Creosote (Creosote, wood)
Cresols (Cresylic acid) (Phenol, methyl-)
Crotonaldehyde (2-Butenal)
Cyanides (soluble salts and complexes), N.O.S.*
Cyanogen (Ethanedinitrile)
Cyanogen bromide (Bromine cyanide)
Cyanogen chloride (Chlorine cyanide)
Cycasin (beta-D-Glucopyranoside, (methyl-ONN-azoxy)methyl-)
2-Cyclohexyl-4,6-dinitrophenol (Phenol, 2-cyclohexyl-4,6-dinitro-)
Cyclophosphamide (2H-1,3,2-Oxazaphosphorine, [bis(2-chloroethyl)amino]-tetrahydro-, 2-oxide)
Daunomycin (5,12-Naphthacenedione, (8S-cis)-8-acetyl-10-[(3-amino-2,3,6-trideoxy)-alpha-L-lyxo-hexopyranosyl]oxy]-7,8,9,10-tetrahydro-6,8,11-trihydroxy-1-methoxy-)
DDD (Dichlorodiphenyldichloroethane) (Ethane, 1,1-dichloro-2,2-bis(p-chlorophenyl)-)
DDE (Ethylene, 1,1-dichloro-2,2-bis[4-chlorophenyl]-)
DDT (Dichlorodiphenyltrichloroethane) (Ethane, 1,1,1-trichloro-2,2-bis(p-chlorophenyl)-)
Diallate (S-(2,3-dichloroallyl) diisopropylthiocarbamate)
Dibenz[a,h]acridine (1,2,5,6-Dibenzacridine)
Dibenz[a,j]acridine (1,2,7,8-Dibenzacridine)
Dibenz[a,h]anthracene (1,2,5,6-Dibenzanthracene)
7H-Dibenzo[c,g]carbazole (3,4,5,6-Dibenzcarbazole)
Dibenzo[a,e]pyrene (1,2,4,5-Dibenzpyrene)
Dibenzo[a,h]pyrene (1,2,5,6-Dibenzpyrene)
Dibenzo[a,i]pyrene (1,2,7,8-Dibenzpyrene)
1,2-Dibromo-3-chloropropane (Propane, 1,2-dibromo-3-chloro-)
1,2-Dibromoethane (Ethylene dibromide)
Dibromomethane (Methylene bromide)
Di-n-butyl phthalate (1,2-Benzenedicarboxylic acid, dibutyl ester)
o-Dichlorobenzene (Benzene, 1,2-dichloro-)
m-Dichlorobenzene (Benzene, 1,3-dichloro-)
p-Dichlorobenzene (Benzene, 1,4-dichloro-)
Dichlorobenzene, N.O.S.* (Benzene, dichloro-, N.O.S.*)
3,3'-Dichlorobenzidine ([1,1'-Biphenyl]-4,4'-diamine, 3,3'-dichloro-)
1,4-Dichloro-2-butene (2-Butene, 1,4-dichloro-)
Dichlorodifluoromethane (Methane, dichlorodifluoro-)

* The abbreviation N.O.S. (not otherwise specified) signifies those members of the general class not specifically listed by name in this appendix.

TABLE 1 (continued)

1,1-Dichloroethane (Ethylidene dichloride)
1,2-Dichloroethane (Ethylene dichloride)
trans-1,2-Dichloroethene (1,2-Dichloroethylene)
Dichloroethylene, N.O.S.* (Ethene, dichloro-, N.O.S.*)
1,1-Dichloroethylene (Ethene, 1,1-dichloro-)
Dichloromethane (Methylene chloride)
2,4-Dichlorophenol (Phenol, 2,4-dichloro-)
2,6-Dichlorophenol (Phenol, 2,6-dichloro-)
2,4-Dichlorophenoxyacetic acid (2,4-D), salts and esters (Acetic acid, 2,4-dichlorophenoxy-, salts and esters)
Dichlorophenylarsine (Phenyl dichloroarsine)
Dichloropropane, N.O.S.* (Propane, dichloro-, N.O.S.*)
1,2-Dichloropropane (Propylene dichloride)
Dichloropropanol, N.O.S.* (Propanol, dichloro-, N.O.S.*)
Dichloropropene, N.O.S.* (Propene, dichloro-, N.O.S.*)
1,3-Dichloropropene (1-Propene, 1,3-dichloro-)
Dieldrin (1,2,3,4,10,10-hexachloro-6,7-epoxy-1,4,4a,5,6,7,8,8a-octa-hydro-endo,exo-1,4:5,8-Dimethanonaphthalene)
1,2:3,4-Diepoxybutane (2,2'-Bioxirane)
Diethylarsine (Arsine, diethyl-)
N,N-Diethylhydrazine (Hydrazine, 1,2-diethyl)
O,O-Diethyl S-methyl ester of phosphorodithioic acid (Phosphorodithioic acid, O,O-diethyl S-methyl ester
O,O-Diethylphosphoric acid, O-p-nitrophenyl ester (Phosphoric acid, diethyl p-nitrophenyl ester)
Diethyl phthalate (1,2-Benzenedicarboxylic acid, diethyl ester)
O,O-Diethyl O-2-pyrazinyl phosphorothioate (Phosphorothioic acid, O,O-diethyl O-pyrazinyl ester
Diethylstilbesterol (4,4'-Stilbenediol, alpha,alpha-diethyl, bis(dihydrogen phosphate, (E)-)
Dihydrosafrole (Benzene, 1,2-methylenedioxy-4-propyl-)
3,4-Dihydroxy-alpha-(methylamino)methyl benzyl alcohol (1,2-Benzenediol, 4-[1-hydroxy-2-(methylamino)ethyl]-)
Diisopropylfluorophosphate (DFP) (Phosphorofluoridic acid, bis(1-methylethyl) ester)
Dimethoate (Phosphorodithioic acid, O,O-dimethyl S-[2-(methylamino)-2-oxoethyl] ester
3,3'-Dimethoxybenzidine ([1,1'-Biphenyl]-4,4'diamine, 3,3'-dimethoxy-)
p-Dimethylaminoazobenzene (Benzenamine, N,N-dimethyl-4-(phenylazo)-)
7,12-Dimethylbenz[a]anthracene (1,2-Benzanthracene, 7,12-dimethyl-)
3,3'-Dimethylbenzidine ([1,1'-Biphenyl]-4,4'-diamine, 3,3'-dimethyl-)
Dimethylcarbamoyl chloride (Carbamoyl chloride, dimethyl-)
1,1-Dimethylhydrazine (Hydrazine, 1,1-dimethyl-)
1,2-Dimethylhydrazine (Hydrazine, 1,2-dimethyl-)
3,3-Dimethyl-1-(methylthio)-2-butanone, O-[(methylamino) carbonyl]oxime (Thiofanox)
alpha,alpha-Dimethylphenethylamine (Ethanamine, 1,1-dimethyl-2-phenyl-)
2,4-Dimethylphenol (Phenol, 2,4-dimethyl-)
Dimethyl phthalate (1,2-Benzenedicarboxylic acid, dimethyl ester)
Dimethyl sulfate (Sulfuric acid, dimethyl ester)
Dinitrobenzene, N.O.S.* (Benzene, dinitro-, N.O.S.*)
4,6-Dinitro-o-cresol and salts (Phenol, 2,4-dinitro-6-methyl-, and salts)
2,4-Dinitrophenol (Phenol, 2,4-dinitro-)
2,4-Dinitrotoluene (Benzene, 1-methyl-2,4-dinitro-)
2,6-Dinitrotoluene (Benzene, 1-methyl-2,6-dinitro-)
Di-n-octyl phthalate (1,2-Benzenedicarboxylic acid, dioctyl ester)
1,4-Dioxane (1,4-Diethylene oxide)
Diphenylamine (Benzenamine, N-phenyl-)
1,2-Diphenylhydrazine (Hydrazine, 1,2-diphenyl-)
Di-n-propylnitrosamine (N-Nitroso-di-n-propylamine)
Disulfoton (O,O-diethyl S-[2-(ethylthio)ethyl] phosphorodithioate)
2,4-Dithiobiuret (Thioimidodicarbonic diamide)
Endosulfan (5-Norbornene, 2,3-dimethanol, 1,4,5,6,7,7-hexachloro-, cyclic sulfite)
Endrin and metabolites (1,2,3,4,10,10-hexachloro-6,7-epoxy-1,4,4a,5,6,7,8,8a-octahydro-endo,endo-1,4:5,8-dimethanonaphthalene, and metabolites)
Ethyl carbamate (Urethan) (Carbamic acid, ethyl ester)
Ethyl cyanide (propanenitrile)
Ethylenebisdithiocarbamic acid, salts and esters (1,2-Ethanediylbiscarbamodithioic acid, salts and esters
Ethyleneimine (Aziridine)
Ethylene oxide (Oxirane)
Ethylenethiourea (2-Imidazolidinethione)
Ethyl methacrylate (2-Propenoic acid, 2-methyl-, ethyl ester)
Ethyl methanesulfonate (Methanesulfonic acid, ethyl ester)
Fluoranthene (Benzo[j,k]fluorene)
Fluorine
2-Fluoroacetamide (Acetamide, 2-fluoro-)
Fluoroacetic acid, sodium salt (Acetic acid, fluoro-, sodium salt)
Formaldehyde (Methylene oxide)
Formic acid (Methanoic acid)
Glycidylaldehyde (1-Propanol-2,3-epoxy)
Halomethane, N.O.S.*
Heptachlor (4,7-Methano-1H-indene, 1,4,5,6,7,8,8-heptachloro-3a,4,7,7a-tetrahydro-)
Heptachlor epoxide (alpha, beta, and gamma isomers) (4,7-Methano-1H-indene, 1,4,5,6,7,8,8-heptachloro-2,3-epoxy-3a,4,7,7-tetrahydro-, alpha, beta, and gamma isomers)
Hexachlorobenzene (Benzene, hexachloro-)
Hexachlorobutadiene (1,3-Butadiene, 1,1,2,3,4,4-hexachloro-)
Hexachlorocyclohexane (all isomers) (Lindane and isomers)
Hexachlorocyclopentadiene (1,3-Cyclopentadiene, 1,2,3,4,5,5-hexachloro-)
Hexachloroethane (Ethane, 1,1,1,2,2,2-hexachloro-)
1,2,3,4,10,10-Hexachloro-1,4,4a,5,8,8a-hexahydro-1,4:5,8-endo,endo-dimethanonaphthalene (Hexachlorohexahydro-endo,endo-dimethanonaphthalene)
Hexachlorophene (2,2'-Methylenebis(3,4,6-trichlorophenol))
Hexachloropropene (1-Propene, 1,1,2,3,3,3-hexachloro-)
Hexaethyl tetraphosphate (Tetraphosphoric acid, hexaethyl ester)
Hydrazine (Diamine)
Hydrocyanic acid (Hydrogen cyanide)
Hydrofluoric acid (Hydrogen fluoride)
Hydrogen sulfide (Sulfur hydride)
Hydroxydimethylarsine oxide (Cacodylic acid)
Indeno(1,2,3-cd)pyrene (1,10-(1,2-phenylene)pyrene)
Iodomethane (Methyl iodide)
Iron dextran (Ferric dextran)
Isocyanic acid, methyl ester (Methyl isocyanate)
Isobutyl alcohol (1-Propanol, 2-methyl-)
Isosafrole (Benzene, 1,2-methylenedioxy-4-allyl-)
Kepone (Decachlorooctahydro-1,3,4-Methano-2H-cyclobuta[cd]pentalen-2-one)
Lasiocarpine (2-Butenoic acid, 2-methyl-, 7-[(2,3-dihydroxy-2-(1-methoxyethyl)-3-methyl-1-oxobutoxy)methyl]-2,3,5,7a-tetrahydro-1H-pyrrolizin-1-yl ester)
Lead and compounds, N.O.S.*
Lead acetate (Acetic acid, lead salt)
Lead phosphate (Phosphoric acid, lead salt)
Lead subacetate (Lead, bis(acetato-O)tetrahydroxytri-)
Maleic anhydride (2,5-Furandione)
Maleic hydrazide (1,2-Dihydro-3,6-pyridazinedione)
Malononitrile (Propanedinitrile)
Melphalan (Alanine, 3-[p-bis(2-chloroethyl)amino]phenyl-, L-)
Mercury fulminate (Fulminic acid, mercury salt)
Mercury and compounds, N.O.S.*
Methacrylonitrile (2-Propenenitrile, 2-methyl-)
Methanethiol (Thiomethanol)
Methapyrilene (Pyridine, 2-[(2-dimethylamino)ethyl]-2-thenylamino-)
Methomyl (Acetimidic acid, N-[(methylcarbamoyl)oxy]thio-, methyl ester
Methoxychlor (Ethane, 1,1,1-trichloro-2,2'-bis(p-methoxyphenyl)-)
2-Methylaziridine (1,2-Propylenimine)
3-Methylcholanthrene (Benz[j]aceanthrylene, 1,2-dihydro-3-methyl-)
Methyl chlorocarbonate (Carbonochloridic acid, methyl ester)
4,4'-Methylenebis(2-chloroaniline) (Benzenamine, 4,4'-methylenebis-(2-chloro-)
Methyl ethyl ketone (MEK) (2-Butanone)
Methyl hydrazine (Hydrazine, methyl-)
2-Methyllactonitrile (Propanenitrile, 2-hydroxy-2-methyl-)
Methyl methacrylate (2-Propenoic acid, 2-methyl-, methyl ester)
Methyl methanesulfonate (Methanesulfonic acid, methyl ester)
2-Methyl-2-(methylthio)propionaldehyde-o-(methylcarbonyl) oxime (Propanal, 2-methyl-2-(methylthio)-, O-[(methylamino)carbonyl]oxime)

TABLE 1 (continued)

N-Methyl-N'-nitro-N-nitrosoguanidine (Guanidine, N-nitroso-N-methyl-N'-nitro-)
Methyl parathion (O,O-dimethyl O-(4-nitrophenyl) phosphorothioate)
Methylthiouracil (4-1H-Pyrimidinone, 2,3-dihydro-6-methyl-2-thioxo-)
Mustard gas (Sulfide, bis(2-chloroethyl)-)
Naphthalene
1,4-Naphthoquinone (1,4-Naphthalenedione)
1-Naphthylamine (alpha-Naphthylamine)
2-Naphthylamine (beta-Naphthylamine)
1-Naphthyl-2-thiourea (Thiourea, 1-naphthalenyl-)
Nickel and compounds, N.O.S.*
Nickel carbonyl (Nickel tetracarbonyl)
Nickel cyanide (Nickel (II) cyanide)
Nicotine and salts (Pyridine, (S)-3-(1-methyl-2-pyrrolidinyl)-, and salts)
Nitric oxide (Nitrogen (II) oxide)
p-Nitroaniline (Benzenamine, 4-nitro-)
Nitrobenzine (Benzene, nitro-)
Nitrogen dioxide (Nitrogen (IV) oxide)
Nitrogen mustard and hydrochloride salt (Ethanamine, 2-chloro-, N-(2-chloroethyl)-N-methyl-, and hydrochloride salt)
Nitrogen mustard N-Oxide and hydrochloride salt (Ethanamine, 2-chloro-, N-(2-chloroethyl)-N-methyl-, and hydrochloride salt)
Nitroglycerine (1,2,3-Propanetriol, trinitrate)
4-Nitrophenol (Phenol, 4-nitro-)
4-Nitroquinoline-1-oxide (Quinoline, 4-nitro-1-oxide-)
Nitrosamine, N.O.S.*
N-Nitrosodi-n-butylamine (1-Butanamine, N-butyl-N-nitroso-)
N-Nitrosodiethanolamine (Ethanol, 2,2'-(nitrosoimino)bis-)
N-Nitrosodiethylamine (Ethanamine, N-ethyl-N-nitroso-)
N-Nitrosodimethylamine (Dimethylnitrosamine)
N-Nitroso-N-ethylurea (Carbamide, N-ethyl-N-nitroso-)
N-Nitrosomethylethylamine (Ethanamine, N-methyl-N-nitroso-)
N-Nitroso-N-methylurea (Carbamide, N-methyl-N-nitroso-)
N-Nitroso-N-methylurethane (Carbamic acid, methylnitroso-, ethyl ester)
N-Nitrosomethylvinylamine (Ethenamine, N-methyl-N-nitroso-)
N-Nitrosomorpholine (Morpholine, N-nitroso-)
N-Nitrosonornicotine (Nornicotine, N-nitroso-)
N-Nitrosopiperidine (Pyridine, hexahydro-, N-nitroso-)
Nitrosopyrrolidine (Pyrrole, tetrahydro-, N-nitroso-)
N-Nitrososarcosine (Sarcosine, N-nitroso-)
5-Nitro-o-toluidine (Benzenamine, 2-methyl-5-nitro-)
Octamethylpyrophosphoramide (Diphosphoramide, octamethyl-)
Osmium tetroxide (Osmium (VIII) oxide)
7-Oxabicyclo[2.2.1]heptane-2,3-dicarboxylic acid (Endothal)
Paraldehyde (1,3,5-Trioxane, 2,4,6-trimethyl-)
Parathion (Phosphorothioic acid, O,O-diethyl O-(p nitrophenyl) ester
Pentachlorobenzene (Benzene, pentachloro-)
Pentachloroethane (Ethane, pentachloro-)
Pentachloronitrobenzene (PCNB) (Benzene, pentachloronitro-)
Pentachlorophenol (Phenol, pentachloro-)
Phenacetin (Acetamide, N-(4-ethoxyphenyl)-)
Phenol (Benzene, hydroxy-)
Phenylenediamine (Benzenediamine)
Phenylmercury acetate (Mercury, acetatophenyl-)
N-Phenylthiourea (Thiourea, phenyl-)
Phosgene (Carbonyl chloride)
Phosphine (Hydrogen phosphide)
Phosphorodithioic acid, O,O-diethyl S-[(ethylthio)methyl] ester (Phorate)
Phosphorothioic acid, O,O-dimethyl O-[p-[(dimethylamino)sulfonyl]phenyl] ester (Famphur)
Phthalic acid esters, N.O.S.* (Benzene, 1,2-dicarboxylic acid, esters, N.O.S.*)
Phthalic anhydride (1,2-Benzenedicarboxylic acid anhydride)
2-Picoline (Pyridine, 2-methyl-)
Polychlorinated biphenyl, N.O.S.*
Potassium cyanide
Potassium silver cyanide (Argentate(1-), dicyano-, potassium)
Pronamide (3,5-Dichloro-N-(1,1-dimethyl-2-propynyl)benzamide)
1,3-Propane sultone (1,2-Oxathiolane, 2,2-dioxide)
n-Propylamine (1-Propanamine)
Propylthiouracil (Undecamethylenediamine, N,N'-bis(2-chlorobenzyl)-, dihydrochloride)
2-Propyn-1-ol (Propargyl alcohol)
Pyridine
Reserpine (Yohimban-16-carboxylic acid, 11,17-dimethoxy-18-[(3,4,5-trimethoxybenzoyl)oxy]-, methyl ester)
Resorcinol (1,3-Benzenediol)
Saccharin and salts (1,2-Benzoisothiazolin-3-one, 1,1-dioxide, and salts)
Safrole (Benzene, 1,2-methylenedioxy-4-allyl-)
Selenious acid (Selenium dioxide)
Selenium and compounds, N.O.S.*
Selenium sulfide (Sulfur selenide)
Selenourea (Carbamimidoselenoic acid)
Silver and compounds, N.O.S.*
Silver cyanide
Sodium cyanide
Streptozotocin (D-Glucopyranose, 2-deoxy-2-(3-methyl-3-nitrosoureido)-)
Strontium sulfide
Strychnine and salts (Strychnidin-10-one, and salts)
1,2,4,5-Tetrachlorobenzene (Benzene, 1,2,4,5-tetrachloro-)
2,3,7,8-Tetrachlorodibenzo-p-dioxin (TCDD) (Dibenzo-p-dioxin, 2,3,7,8-tetrachloro-)
Tetrachloroethane, N.O.S.* (Ethane, tetrachloro-, N.O.S.*)
1,1,1,2-Tetrachlorethane (Ethane, 1,1,1,2-tetrachloro-)
1,1,2,2-Tetrachlorethane (Ethane, 1,1,2,2-tetrachloro-)
Tetrachloroethylene (Ethene, 1,1,2,2-tetrachloro-)
Tetrachloromethane (Carbon tetrachloride)
2,3,4,6,-Tetrachlorophenol (Phenol, 2,3,4,6-tetrachloro-)
Tetraethyldithiopyrophosphate (Dithiopyrophosphoric acid, tetraethyl-ester)
Tetraethyl lead (Plumbane, tetraethyl-)
Tetraethylpyrophosphate (Pyrophosphoric acide, tetraethyl ester)
Tetranitromethane (Methane, tetranitro-)
Thallium and compounds, N.O.S.*
Thallic oxide (Thallium (III) oxide)
Thallium (I) acetate (Acetic acid, thallium (I) salt)
Thallium (I) carbonate (Carbonic acid, dithallium (I) salt)
Thallium (I) chloride
Thallium (I) nitrate (Nitric acid, thallium (I) salt)
Thallium selenite
Thallium (I) sulfate (Sulfuric acid, thallium (I) salt)
Thioacetamide (Ethanethioamide)
Thiosemicarbazide (Hydrazinecarbothioamide)
Thiourea (Carbamide thio-)
Thiuram (Bis(dimethylthiocarbamoyl) disulfide)
Toluene (Benzene, methyl-)
Toluenediamine (Diaminotoluene)
o-Toluidine hydrochloride (Benzenamine, 2-methyl-, hydrochloride)
Tolylene diisocyanate (Benzene, 1,3-diisocyanatomethyl-)
Toxaphene (Camphene, octachloro-)
Tribromomethane (Bromoform)
1,2,4-Trichlorobenzene (Benzene, 1,2,4 trichloro-)
1,1,1-Trichloroethane (Methyl chloroform)
1,1,2-Trichloroethane (Ethane, 1,1,2 trichloro-)
Trichloroethene (Trichloroethylene)
Trichloromethanethiol (Methanethiol, trichloro-)
Trichloromonofluoromethane (Methane trichlorofluoro-)
2,4,5-Trichlorophenol (Phenol, 2,4,5 trichloro-)
2,4,6-Trichlorophenol (Phenol, 2,4,6-trichloro-)
2,4,5-Trichlorophenoxyacetic acid (2,4,5-T) (Acetic acid, 2,4,5-trichlorophenoxy-)
2,4,5-Trichlorophenoxypropionic acid (2,4,5-TP) (Silvex) (Propionoic acid, 2-(2,4,5-trichlorophenoxy)-)
Trichloropropane, N.O.S.* (Propane trichloro-, N.O.S.*)
1,2,3-Trichloropropane (Propane, 1,2,3-trichloro-)
O,O,O-Triethyl phosphorothioate (Phosphorothioic acid, O,O,O-triethyl ester)
sym-Trinitrobenzene (Benzene, 1,3,5-trinitro-)
Tris(1-azridinyl) phosphine sulfide (Phosphine sulfide, tris(1-aziridinyl-)
Tris(2,3-dibromopropyl) phosphate (1-Propanol, 2,3-dibromo-, phosphate)
Trypan blue (2,7-Naphthalenedisulfonic acid, 3,3'-[(3,3'-dimethyl[1,1'-biphenyl]-4,4'-diyl)bis(azo)]bis(5-amino-4-hydroxy-, tetrasodium salt)
Uracil mustard (Uracil 5-[bis(2-chloroethyl)amino]-)
Vanadic acid, ammonium salt (ammonium vanadate)
Vanadium pentoxide (Vanadium (V) oxide)
Vinyl chloride (Ethene, chloro-)
Zinc cyanide
Zinc phosphide

This review will serve to highlight the advantages and disadvantages of waste incineration that must be taken into account before the decision to incinerate a waste is taken.

Three elements contained in many hazardous wastes are especially noteworthy since they generate heat when completely oxidized or combusted. These elements and their heats of combustion (expressed as Btu per pound of pure substance) are carbon (14,096 Btu/lb), hydrogen (61,031 Btu/lb) and sulfur (3,984 Btu/lb).[4] Compounds that contain these elements may release heat upon combustion, although the exact heat release potential of any complex compound cannot be simply calculated from the composition of the compound due to the varying strength of the chemical bonds which may require significant amounts of energy to break. Nonetheless, a prime goal of incineration is to maximize the heat release by providing for complete combustion of these substances. Carbon, when completely oxidized, will form carbon dioxide (CO_2) and provide for the maximum release of energy. If insufficient oxygen is available for combustion, then carbon will oxidize to carbon monoxide (CO) or not oxidize at all and form a particulate emission of carbon particles, thereby not only creating two atmospheric pollutants, but resulting in less heat release, as unburned carbon releases no energy and carbon forms CO with a release of only 3960 Btu/lb, a reduction of 72 percent when compared to the heat released when CO_2 is formed. Similarly, if sufficient oxygen is available, hydrogen will combust to water (H_2O) and sulfur to sulfur dioxide (SO_2), and to a lesser extent sulfur trioxide (SO_3). The amount of sulfur dioxide and sulfur trioxide produced is directly proportional to the sulfur content of the waste material. Forty six of the Appendix VIII substances contain sulfur. This constitutes approximately 12 percent of these compounds. The sulfur composition of these forty-six compounds ranges from 8 to over 90 percent, so the potential for a high SO_2 concentration in the incinerator flue gas exists if a pure stream of a substance such as hydrogen sulfide (H_2S-94%S) is burned.

Incomplete combustion of sulfur compounds will also form intermediate combustion products such as hydrogen sulfide (H_2S). As with carbon, less heat will be released and atmospheric pollutants will be created. Providing an ideal combustion environment, where sufficient oxygen is available to produce only carbon dioxide, water, and sulfur dioxide from the combustion of carbon, hydrogen and sulfur, is an important aspect of hazardous waste, or for that matter, any type of incineration. Such an environment will maximize heat release and minimize unnecessary pollutant formation.

Understanding this basic combustion principle is important since approximately 90 percent of the Appendix VIII compounds contain carbon, 82 percent contain hydrogen and 12 percent contain sulfur. (Many compounds contain more than one of these compounds; for example, 298 of the 375 Appendix VIII hazardous constituents, or 80 percent contain both hydrogen and carbon). The presence of carbon in a material by definition makes that an organic substance. The complete combustion of a simple Appendix VIII organic waste material such as toluene (C_7H_8) is relatively easy to effect and results in the formation of carbon dioxide and water plus the release of heat.

However, as the organic molecule becomes larger and additional elements become attached, complete combustion becomes more difficult and the number of actual and potential combustion products grows.

The fate of other elements in hazardous wastes is also important in order to determine the make-up of incinerator combustion gases. Approximately 39 percent of the Appendix VIII wastes contain nitrogen. When combusted, this nitrogen will either be released in the form of elemental nitrogen, N_2, or will form one of the many oxides of nitrogen primarily nitric oxide (NO) and nitrogen dioxide (NO_2). It is interesting to note that both NO and NO_2 are Appendix VIII substances and therefore defined as hazardous for this report. All nitrogen oxides will be collectively referred to as NO_x, without specific identification of the different oxide forms. The distinction between NO and NO_2 is not critical from an emissions viewpoint; however it is important for designers of air pollution control equipment. Nitrogen oxide formations will occur from both bound nitrogen contained in the fuel (fuel NO_x) and nitrogen contained in the atmospheric air which is supplied to the incinerator for waste combustion (thermal NO_x). Research to date on the formation of fuel NO_x has concentrated on conventional fuels such as residual oil (0.2 to 0.8 percent by weight bound nitrogen) and coal (typically 1 to 2 percent nitrogen).[5] This work has demonstrated that fuels with higher nitrogen contents produce more fuel NO_x, although the exact formation mechanism and the specific increase in fuel NO_x that results from a known increase in fuel nitrogen content is not completely understood at this time. While the overall contribution of fuel NO_x to total NO_x may not be necessarily significant with conventional fuels, it can play an important role in NO_x from hazardous waste incinerators. Certain Appendix VIII wastes contain large amounts of nitrogen (e.g., hydrazine-H_4N_2-87.5%N) and if these compounds form the primary waste feed to an incinerator, substantial amounts of nitrogen oxide emissions may result. One source estimates that for chemical waste incineration, roughly 5 to 10 percent of organic bound nitrogen will form nitrogen oxides,[6] although this estimate could not be confirmed. Special incineration systems have been designed to treat potentially high NO_x wastes. Such systems utilize a reduction furnace immediately after the primary incineration chamber in order to reduce NO_x to elemental nitrogen, N_2.[2]

The formation mechanisms associated with thermal NO_x are more clearly understood. Thermal NO_x emission rates are dependent on factors such as peak flame temperatures, gas residence time at peak flame temperatures and the amount of atomic oxygen available at high temperatures.[5] These interrelationships are graphically displayed in Figure 1. Hazardous wastes play an indirect role in thermal NO_x formation. Compounds that are especially stable require higher incinerator temperatures for complete destruction. These higher temperatures will then result in the formation of more NO_x, regardless of the composition of the compound being destroyed. To minimize total NO_x formation, a hazardous waste incinerator should therefore be operated at the lowest possible temperature that is necessary to provide for complete destruction of the waste material.

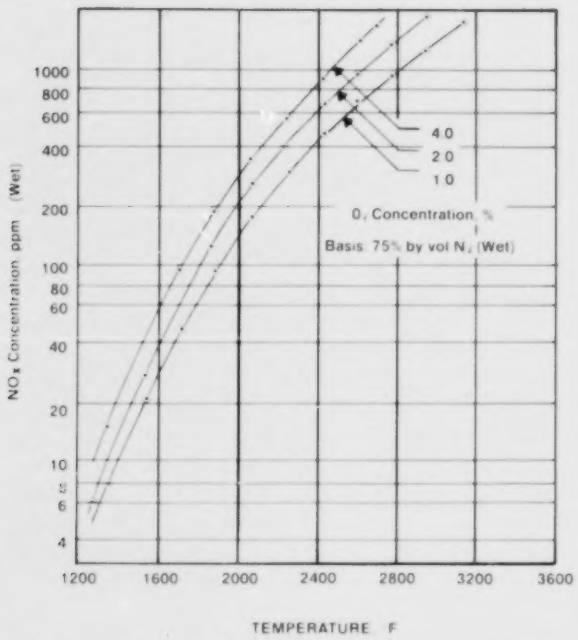

Figure 1. Equilibrium NO_x concentration.[7]

Another major subclass of Appendix VIII hazardous wastes are the halogens, which include chlorine, fluorine, bromine and iodine. The principal element of concern in this group is chlorine. Chlorine compounds, specifically chlorinated organics, comprise approximately 28 percent of the Appendix VIII hazardous constituents. The importance of these compounds is underscored by the fact that current RCRA Regulations for incinerators (40 CFR 264, Subpart O) specifically address the burning of chlorinated compounds. The performance standards for hazardous waste incinerators included in these regulations requires that "an incinerator burning hazardous waste containing more than 0.5 percent chlorine must remove 99 percent of the hydrogen chloride from the exhaust gas."[8]

The combustion of a waste containing chlorine will result in the formation of either free chlorine, Cl_2, or hydrogen chloride, HCl, depending on the amount of hydrogen available and a number of other factors. Since hydrogen chloride and other hydrogen halides are more readily scrubbed from combustion gases than the halogens themselves, sufficient hydrogen should be provided for this equilibrium conversion to take place. If the waste itself contains insufficient hydrogen, auxilliary fuel or steam injection is needed to supply the necessary hydrogen equivalents. The stoichiometric (absolute minimum) requirements are 1 lb H_2 per 35.5 lb Cl_2 and 1 lb H_2 per 19 lb F_2 in the waste.[9]

Due to this hydrogen requirement, the chlorine content of a hazardous waste stream is closely monitored, and chlorinated wastes will be blended with nonchlorinated substances to maintain the desired chlorine and hydrogen ratios.

Another reason why hazardous waste streams, especially chlorinated wastes, are blended concerns the heating value of the waste mixture. The heating value of a waste corresponds to the quantity of heat released when the waste is burned, commonly expressed in Btu/lb. Just as carbon, hydrogen, and sulfur in the pure form release heat upon combustion, so do organic wastes have some finite heating value. To maintain combustion, the amount of heat released by the burning waste must be sufficient to heat incoming waste to its ignition temperature and to provide the energy necessary for the combustion reactions to occur. One goal in hazardous waste incineration is to blend wastes so that their combustion is self-sustaining and no auxilliary fuel is required, thereby minimizing operating costs. While sustained combustion is possible with heating values as low as 4000 Btu/lb (2222 calories/gram), the generally accepted minimal heating value that is required to sustain combustion without the use of auxilliary fuel is 8000 Btu/lb (4444 calories/gram).[9,10]

The heating value of an organic waste will decrease if the moisture and/or chlorine (or other halogen) content increases. Water has no heating value and, in fact, withdraws heat from the system as it is vaporized and heated up to the incinerator temperature. Chlorine also has no heating value and the greater the percentage of chlorine in a waste, the lower will be its heating content, although there is no simple mathematical relationship. Figure 2 shows an empirical relationship between heating value and chlorine content for pure substances. It is common practice in hazardous waste incineration to blend wastes so that the chlorine content does not exceed 30 percent. This is done to maintain sufficient heating value for sustained combustion and to limit free chlorine concentration in the combustion gas.[9]

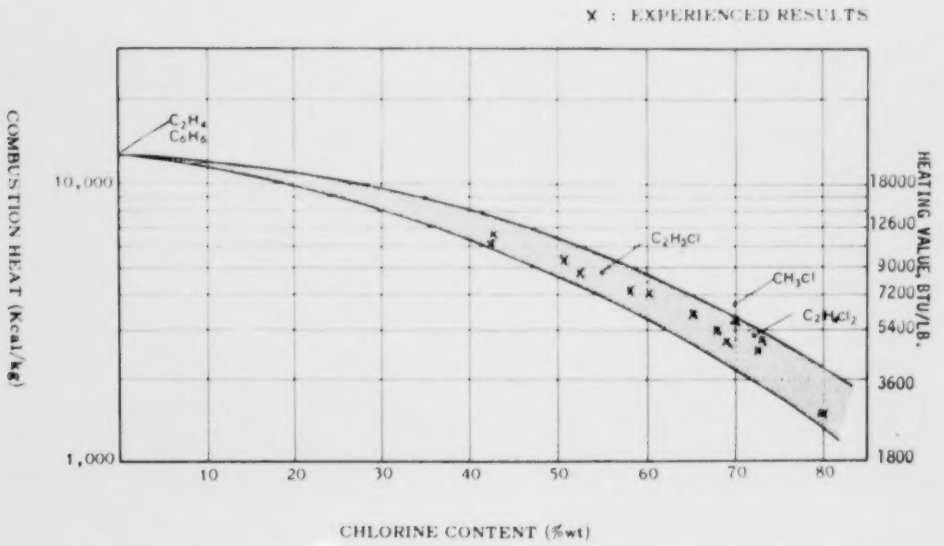

Figure 2. Heat of combustion of chlorinated hydrocarbon.[11]

Phosphorous is another inorganic hazardous waste constituent that requires special considerations. There are 22 Appendix VIII compounds containing this element, and these compounds comprise approximately 6 percent of all hazardous waste constituents. Phosphorous will be oxidized in an incinerator environment to form phosphorous pentoxide, P_2O_5. A gas when formed, P_2O_5 upon cooling forms a phosphoric acid mist with a particle size in the submicron range.[6] This particulate requires a high efficiency air pollution control device for particulate control or a two stage scrubber in which dilute phosphoric acid is used for particulate control in the first stage and some form of acid gas scrubber is used for the second stage.[12] In either case, the cost of emission control equipment can add significantly to the overall incineration system expenditure.

The formation of metallic salts, specifically alkali metal salts, during hazardous waste incineration can cause substantial operating problems by adhering to the internal surfaces of the incineration system. Alkali metal salts, which are the salts of sodium and potassium, will attack the refractory lining of an incinerator.[6,12] Refractory constituents such as chromium, alumina, silicate and magnesia react with the alkali salt to cause spalling of the refractory, which in turn leads to a significant maintenance problem. In addition, a mixture of alkali metal salts can form a eutectic compound that has a lower melting point than either constituent. This can cause significant operating problems, as the eutectic may condense on internal incinerator surfaces causing plugging and fouling.[13] For these reasons, alkali metal compounds are typically segregated from other hazardous wastes and not incinerated. One example of this policy is an industrial source which will not feed residues containing more than 50 ppm sodium or other alkali metals to its hazardous waste incinerator in order to protect the refractory.[14]

The elemental form of eleven metals as well as compounds containing an additional five metals are among the compounds listed in Appendix VIII. Metals have no heating value and when added to an incineration cause a net heat drain since they must be heated to the incineration temperature. In addition, when exposed to the high temperature oxidizing environment of an incinerator, metals will form metallic oxides, which have a small mean particle size, typically less than 5 microns. These fine particles are difficult and costly to clean from the flue gas stream. These factors favor removal of the metal constituents from a hazardous waste stream before incineration.

One additional factor, beyond chemical composition and heat content, that may affect whether an Appendix VIII compound is likely to be incinerated or not is the potential byproducts that may result from incomplete combustion of the compound. Ideally, a hazardous waste incinerator will provide for complete combustion of all materials, producing just CO_2, H_2O, SO_2, NO_x, and some trace amounts of metallic and/or inorganic oxides, depending on the feed composition. However, improper operation and/or design of an incinerator may lead to the emissions of products of incomplete combustion (PIC's). PICs include carbon monoxide, hydrocarbons, aldehydes, ketones, amines, organic acids, polycyclic organic matter (POM) and any other compounds

which escape thermal destruction.[10] PICs can pose a serious environmental hazard in those cases where the original Appendix VIII substance decomposes to a yet more toxic byproduct. Polychlorinated biphenyls (PCBs) can, under certain conditions, form polychlorinated-dibenzo-p-dioxins (PCDD), an extremely lethal substance. Similarly the hazardous material hexachlorocyclopentadiene (HCCPD) is known to decompose into the even more hazardous compound, hexachlorobenzene. The potential for generating such toxic byproducts may play a part in the decision to incinerate a compound, and such potential points out the need for proper design, operation and maintenance of any hazardous waste incineration facility.

In summary, the flue gas composition of a hazardous waste incinerator is largely dependent upon the composition of the waste feed material. Approximately 90 percent of the hazardous waste constituents listed in Appendix VIII are organic, and if properly combusted, will oxidize to primarily carbon dioxide and water. Sulfur oxides will be formed in proportion to the weight of sulfur in the feed material and nitrogen oxide concentrations in the flue gas are dependent upon both feed material composition (fuel NO_x) and incinerator operating temperature (thermal NO_x). Chlorinated compounds, when incinerated, form both free chlorine and hydrogen chloride, with the latter predominating when excess hydrogen is provided. The same holds true for the other halogens. The incineration of certain materials including metals and inorganics is avoided, when possible, due to air pollution considerations, while the alkali metals will cause operating and maintenance problems inside the incinerator if present in excessive levels. Finally, certain complex hazardous wastes may form extremely toxic byproducts if not completely combusted, so optimization of incinerator design and operation is important.

The heating value of a waste stream is a prime concern in determining whether incineration is an economically viable disposal option. Hazardous wastes are blended so that combustion is as self-supporting as possible, and auxiliary fuel requirements are kept to a minimum. Blending of waste streams is also used to minimize the concentrations of materials which are difficult to incinerate, such as inorganics and metals.

There are additional waste related factors that will affect incineration and that have not been addressed here. The generation rate of each waste stream that must be incinerated, its physical state (gas, liquid or solid) and the incinerator operating temperature that is required to ensure complete destruction, will be a key consideration for determining whether an incinerator is used and what type of incinerator will be most effective. The options that are available in this regard will be more fully addressed in the next section. The affect that waste composition has on the decision to incinerate is summarized in Table 2.

TABLE 2. HAZARDOUS WASTE INCINERATION SUMMARY[2]

Waste containing	Incineration category
• Compounds containing metals	poor
• Inorganic compounds	poor
• Unknown percent of chlorine	potential
• Carbon, hydrogen and/or oxygen, <30% by weight chlorine, phosphorus, sulfur, bromine, iodine, or nitrogen	potential
• Carbon, hydrogen, ≤30% by weight chlorine and/or oxygen	good
• Carbon, hydrogen, and/or oxygen	good

SECTION 3

INCINERATORS

The type of incinerator used to dispose of a hazardous waste material will have an influence on the environment to which a continuous emission monitor is exposed. Incinerators operate at different temperatures, pressures and excess air levels and these factors will affect the relative concentrations of flue gas constituents. While a variety of incinerator designs have been used to dispose of hazardous wastes, this discussion will be limited to three principal types currently used by the industry: liquid injection, rotary kiln, and fluidized bed. These units are widely used due to the advantages each type offers. While other, less common incinerator types such as molten salt, pyrolytic and wet air oxidation units have been successfully employed to destroy certain hazardous waste streams, the number of these novel incinerators that are currently in use does not warrant an in-depth process description here. This section will first review the applicable federal incinerator regulations. At a minimum, incineration systems must be designed to meet these standards. The three principal incinerator types will then be discussed with emphasis on how they work, basic system components, and advantages and disadvantages of each.

The Environmental Protection Agency has promulgated regulations under the Resource Conservation and Recovery Act (RCRA) that specifically addresses hazardous waste incinerators (40 CFR Part 264, Subpart O). These regulations require that any incinerator used to destroy hazardous waste must:[8]

- Achieve a destruction and removal efficiency (DRE) of 99.99 percent for each principal organic hazardous constituent (POHC) designated in the incinerator's permit.
- Remove 99 percent of the hydrogen chloride from the exhaust gas if the hazardous waste feed contains more than 0.5 percent chlorine by weight.
- Not emit particulate matter exceeding 180 milligrams per dry standard cubic meter (0.08 grains per dry standard cubic foot) when corrected for 12 percent CO_2.

The principal organic hazardous constituents that are monitored to determine the incinerator's destruction and removal efficiency are selected from the Appendix VIII hazardous constituents list and are established by the EPA

regional office and the incinerator owner/operator based on the type and concentration of wastes that will be burned. Compliance with this and the other incinerator performance requirements is determined by a trial burn for the unit. In addition, operating requirements are designated in the permit which specify acceptable operating limits for carbon monoxide levels in the stack gas, waste and air feed rates, and combustion zone temperatures.

Incinerator requirements have also been set forth in regulations implementing provisions of the Toxic Substances Control Act (TSCA) for polychlorinated biphenyls (40 CFR, Part 761, Subpart E, Annex I).[15] These regulations specify that an incinerator used to dispose of PCBs must meet the following combustion criteria:

- Maintenance of the introduced liquids for a 2 second dwell time at 1200°C (± 100°C) and 3 percent excess oxygen in the stack gas; or

- Maintenance of the introduced liquids for a 1 1/2 second dwell time at 1600°C (± 100°C) and 2 percent excess oxygen in the stack gas.

These PCB Annex I incinerator requirements also require the monitoring of various operating and flue gas composition parameters.

It is important to note that while the RCRA regulations do not specify combustion temperature/residence time values, the PCB regulations do. This is attributed to (1) the extremely high thermal and chemical stability of the PCB compounds which mandates extremely high temperatures to ensure complete destruction of this molecule while ensuring that no toxic byproducts are formed and (2) the extreme difficulty implicit in specifying combustion temperature/residence time values for every Appendix VIII hazardous waste constituent due to the lack of qualitative data on these combustion characteristics. The specific incinerator temperatures that are required for a hazardous waste incinerator are left to the EPA permit writer to decide, based on the constituents of the waste to be burned, the combustion characteristics of that waste and the potential for formation of incomplete combustion products. In addition, the RCRA regulations allow for pollutant removal efficiency as well as destruction efficiency, so the entire incineration system, including control devices, must be reviewed in judging the ability of an installation to destroy and remove Appendix VIII hazardous wastes constituents.

A detailed, step by step review of factors that must be considered in granting a hazardous waste incinerator permit is presented elsewhere in the literature.[9] This overview of the principal hazardous waste incinerator designs is intended as a brief summary of the principal operating characteristics so as to familiarize the reader with the major system components.

LIQUID INJECTION

Liquid injection incinerators are currently the most commonly used type of incinerator used for hazardous waste disposal.[2] A recent survey of the

hazardous waste incinerator industry indicated that approximately 64 percent of all hazardous waste incinerators sold were liquid injection units.[16] This type of incinerator is made in numerous configurations, but they are generally classified as vertical or horizontal units. Figure 3 presents the details of a vertically fired unit while Figure 4 is a schematic of an entire horizontally fired liquid injection incinerator system. The vertically aligned liquid injection units are preferred when wastes are high in inorganic salts and ash contents, while horizontal units may be used with low ash wastes.[10] The liquid injection incinerator is probably the most flexible and labor free type of incinerator due to its compact construction and lack of moving parts. As the name implies, the liquid injection incinerator is confined to waste feeds which exhibit a viscosity less than 10,000 SSU, which is generally the maximum allowed for pumping.[17] Some wastes are solids at room temperature but melt when heated, are pumpable and have viscosities that allow atomization in the liquid waste burner. Effective use of this, or any other combustion device, requires that the waste be relatively homogeneous with a relatively constant heating value. Liquid waste incinerators find applications ranging from complete combustion of non-combustibles such as contaminated water, to combustion of totally organic compounds, such as waste solvents.[17]

Complete combustion of a waste occurs in a liquid injection unit only if the waste is adequately atomized and mixed with the oxygen source. Atomization is usually achieved either mechanically using rotary cup or pressure atomization systems, or via gas fluid nozzles using high pressure air or steam. The combustion chamber is a refractory lined cylinder, with atomized waste fed in at one end and exhaust gases exiting the other. To ensure a reasonably steady and homogeneous waste flow, liquid injection incineration svstems are equipped with waste storage and blending tanks, as is shown in Figure 4.

Typical combustion chamber residence times for these units ranges from 0.5 to 2.0 seconds. The operating temperature will range from 650 to 1750°C (1200 to 3180°F), depending on the destruction requirements of the waste being incinerated.

Table 3 summarizes the relative advantages and disadvantages of liquid injection incinerators.

ROTARY KILN

Rotary kiln incinerators are popular for hazardous waste incineration facilities due to their ability to handle both liquid and solid waste streams. This versatility is a prerequisite for units installed at commercial hazardous waste processing facilities, or at large manufacturing complexes that generate a wide variety of hazardous wastes. They are especially effective when the size or nature of the waste precludes the use of other types of incineration equipment. Specifically, waste material such as glass bottles, cardboard boxes, discarded packing cases, paper and other unmanageable wastes are often co-incinerated in rotary kilns.[17] Figure 5 presents a schematic of a rotary kiln incinerator facility.

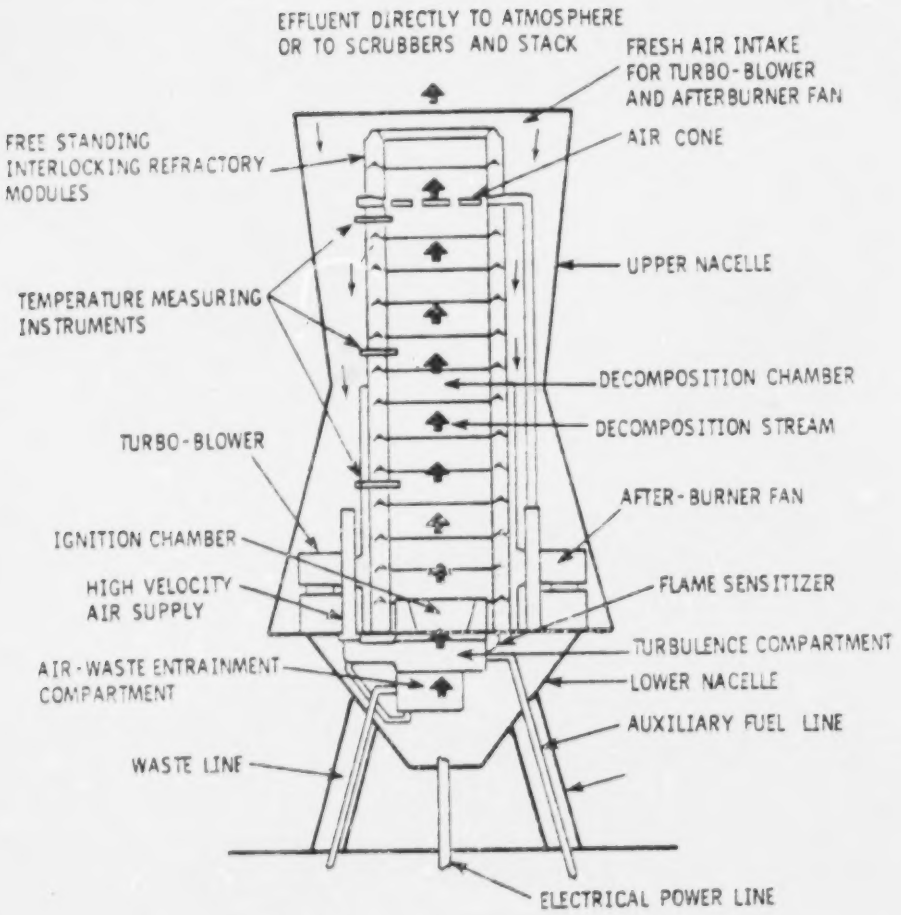

Figure 3. Vertically-fired liquid injection incinerator schematic.[2]

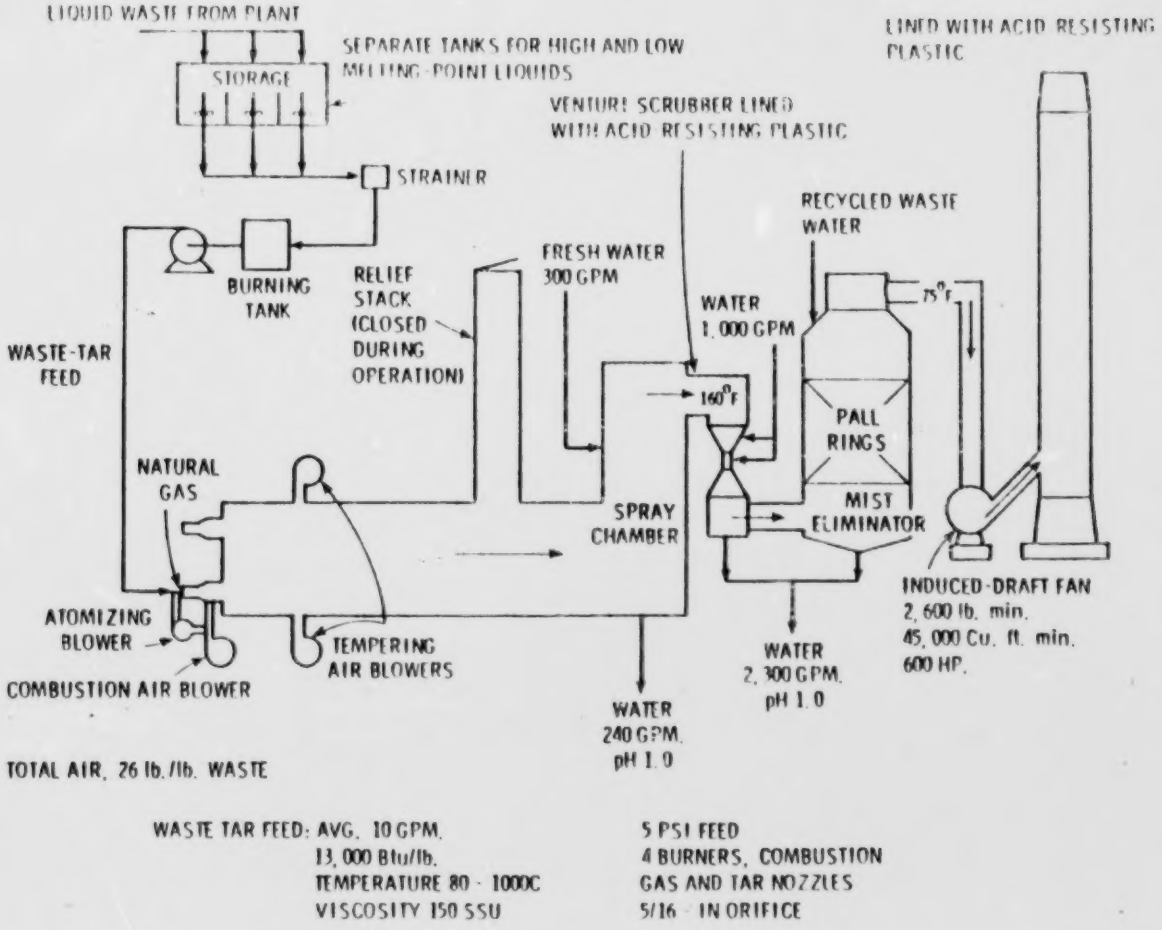

Figure 4. Horizontally-fired liquid injection incinerator schematic.[2]

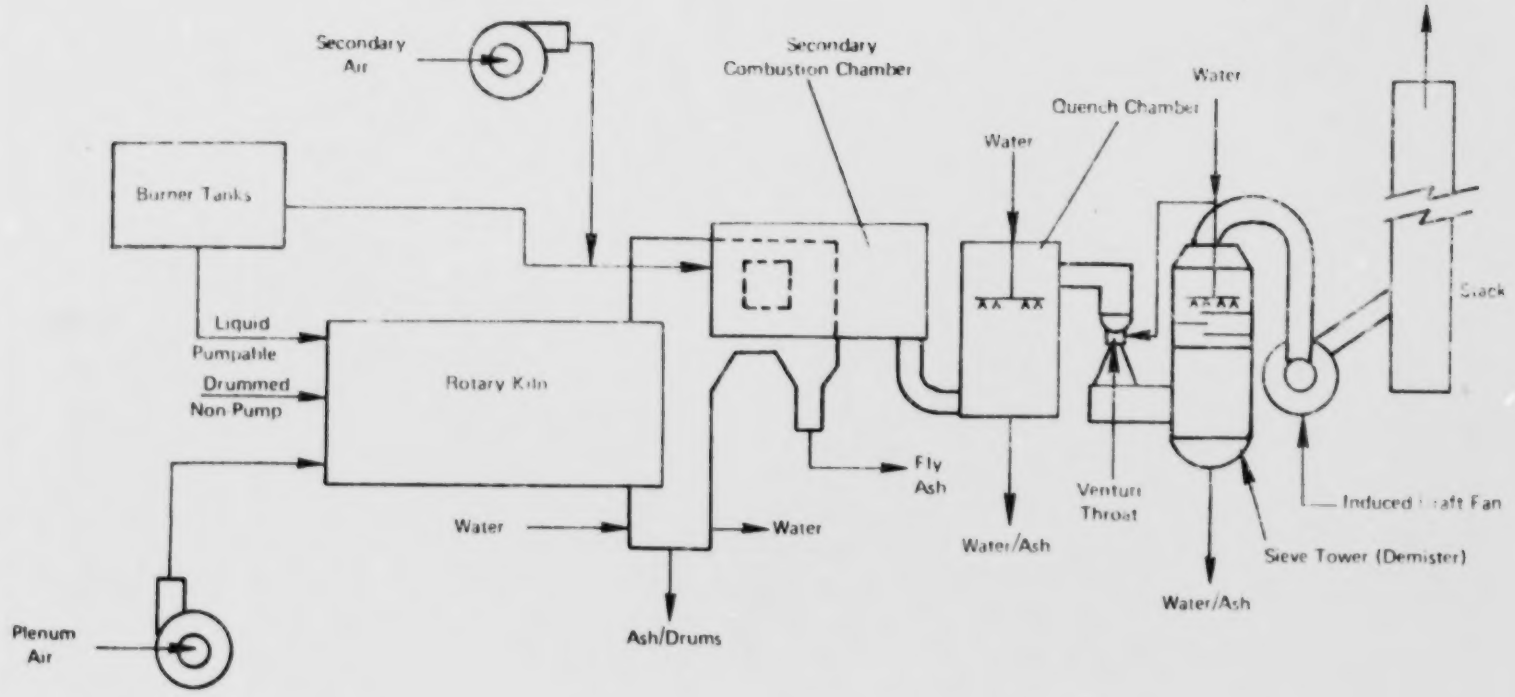

Figure 5. Schematic of rotary kiln facility (courtesy of 3M Company).[18]

TABLE 3. LIQUID INJECTION INCINERATOR ADVANTAGES AND DISADVANTAGES[2]

Advantages

1. Capable of incinerating a wide range of liquid hazardous wastes.
2. No continuous ash removal system is required other than for air pollution control.
3. Capable of a fairly high turndown ratio.
4. Fast temperature response to changes in the waste fuel flowrate.
5. Virtually no moving parts.
6. Low maintenance costs.

Disadvantages

1. Only wastes which can be atomized through a burner nozzle can be incinerated.
2. Heat content of waste burned must maintain adequate ignition and incineration temperatures or a supplemental fuel must be provided.
3. Burners susceptible to pluggage (burners are designed to accept a certain particle size; therefore, particle size is a critical parameter for successful operation).
4. Burner may or may not be able to accept a material which dries and cakes as it passes through the nozzles.

Rotary kiln incinerators are cylindrical, refractory lined shells that are mounted with the axis at a slight incline from the horizontal. This incline, coupled with rotation of the kiln enables solid waste feed material to gradually pass through the unit by gravity and promotes turbulence, waste feed agitation and thorough mixing of the waste with combustion air for maximum waste destruction. It is sometimes necessary to install a secondary high temperature combustion chamber to complete the destruction of vapor phase and particulate matter. This secondary chamber can also be used, without the kiln, if the waste feed material is a flammable liquid. Rotary kilns come in two basic designs: co-current and countercurrent. Co-current units have the auxiliary fuel burner at the front (top) end of the incinerator, at the same end as the waste feed. Countercurrent units have the fuel feed at the lower end of the incinerator, and combustion gases run countercurrent to the flow of waste through the incinerator. Both types will destroy a waste, however, for a waste having low heating value (such as a high water content sludge), the countercurrent design offers the advantage of controlling temperature at both ends which minimizes problems such as overheating the refractory lining.[2] Residence times within the rotary kiln vary from a few seconds for a highly combustible gas to a few hours for a low combustible solid waste. Incinerator temperatures can be varied from 800 to 1600°C (1470 to 2900°F) depending on the requirements of the waste. Solid wastes, sometimes packed in fiber drums are generally fed to the kiln by conveyor. Liquids and sludges are pumped in, with liquids usually strained, then atomized with steam or air.

Table 4 presents a comprehensive list of the relative advantages and disadvantages of rotary kiln incineration. Due to its ability to handle solid, liquid and gaseous wastes, the rotary kiln was the preferred incineration technique for the first two approved commercial hazardous waste incineration facilities operated by Rollins Environmental Systems at Deer Park, Texas and Energy Systems Company at El Dorado, Arkansas. Both units have successfully incinerated obsolete or excess chemical warfare agents and PCB compounds, with PCB destruction efficiencies exceeding 99.99 percent.[19]

FLUIDIZED BED

Fluidized bed incinerators are refractory lined cylindrical vessels that contain a bed of inert, granular material, usually sand. Figure 6 presents a typical fluidized bed schematic. The bed temperature is limited by the softening point of the bed medium, which for sand is about 1100°C (2000°F). Typical fluidized bed incinerator temperatures are in the 450 to 980°C (840 to 1800°F) range.[2] Fluidized air is passed through a distributor plate at a rate sufficiently high to cause the particles in the bed to act as a theoretical fluid. Passage of the waste gases through the bed causes additional agitation and ensures intimate mixing of all waste material with the combustion air. Hazardous waste materials, including waste gases, liquids, slurries and sludges are typically injected into or just above the bed. Normally, bed design restricts combustion to the immediate area of the bed. This maintains the "freeboard" area above the bed for separating of the inert particles from the rising gases and for minor combustion of devolatilized components.

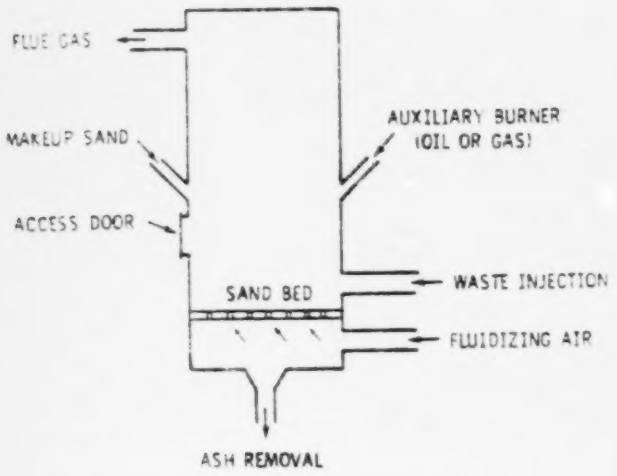

Figure 6. Typical fluidized bed incinerator schematic.[2]

TABLE 4. ROTARY KILN INCINERATORS ADVANTAGES AND DISADVANTAGES[2]

Advantages

1. Will incinerate a wide variety of liquid and solid hazardous wastes.
2. Will incinerate materials passing through a melt phase.
3. Capable of receiving liquids and solids independently or in combination.
4. Feed capability for drums and bulk containers.
5. Adaptable to wide variety of feed mechanism designs.
6. Characterized by high turbulence and air exposure of solid wastes.
7. Continuous ash removal which does not interfere with the waste oxidation.
8. No moving parts inside the kiln (except when chains are added).
9. Adaptable for use with a wet gas scrubbing system.
10. The retention or residence time of the nonvolatile component can be controlled by adjusting the rotational speed.
11. The waste can be fed directly into the kiln without any preparation such as preheating, mixing, etc.
12. Rotary kilns can be operated at temperatures in excess of 2500°F (1400°C), making them well suited for the destruction of toxic compounds that are difficult to thermally degrade.
13. The rotational speed control of the kiln also allows a turndown ratio (maximum to minimum operating range) of about 50 percent.

Disadvantages

1. High capital cost for installation.
2. Operating care necessary to prevent refractory damage; thermal shock is a particularly damaging event.
3. Airborne particles may be carried out of kiln before complete combustion.
4. Spherical or cylindrical items may roll through kiln before complete combustion.
5. The rotary kiln frequently requires additional makeup air due to air leakage via the kiln end seals.
6. Drying or ignition grates, if used prior to the rotary kiln, can cause problems with melt plugging of grates and grate mechanisms.
7. High particulate loadings.
8. Relatively low thermal efficiency.
9. Problems in maintaining seals at either end of the kiln are a significant operating difficulty.
10. Drying of aqueous sludge wastes or melting of some solid wastes can result in clinker or ring formation on refractory walls.

The bed is preheated to start up temperature by a burner located above and impinging on the bed. The large mass (relative to the mass of waste) and high heat content of a bed very rapidly raises the waste to combustion temperatures, which in turn transfers heat to the bed. The residence time of waste material in the bed typically is on the order of 12 to 14 seconds for a liquid hazardous waste.[2]

Fluidized bed incinerators are subject to problems caused by low ash fusion temperatures. This can be avoided by keeping operating temperatures below the ash fusion level or by adding chemicals that raise the fusion temperature of the ash to an acceptable level.[17]

Table 5 presents a list of the relative advantages and disadvantages of fluidized bed incineration.

While there are only a few fluidized bed units now in operation, this number is expected to increase due to the versatility of this device. The bed material can be altered to meet the specific disposal needs of the incinerator operator. For example, limestone may be used as a bed material when organophosphates are incinerated. In this application the limestone acts as a scrubber to capture phosphates from the process creating a nontoxic solid residue rather than a sludge that would result from external scrubbing devices.[20] Similarly, a catalytic bed media can be utilized in the case of an unusually difficult to destruct waste. Sand has been successfully used as the bed media in the incineration of chlorinated and flammable compounds with a total halogen content of fuel in excess of 27 percent.[21] In this application, destruction and removal efficiencies of principal organic hazardous constituent exceeded the required 99.99 percent.

The typical operating ranges for liquid injection, rotary kiln, and fluidized bed incinerators are summarized in Table 6. The selection of a specific unit depends on a variety of factors including capital and operating cost, amount, composition and variability of hazardous waste material and the combustion temperature/residence time destruction requirements of the wastes to be incinerated. As is evident from Table 6, rotary kilns and liquid injection incinerators must be used if the hazardous waste requires high temperature exposure, while fluidized bed units may be the choice if a longer residence time at a lower combustion temperature is sufficient to result in a destruction and removal efficiency in excess of 99.99 percent. Therefore, continuous emission monitoring equipment that is to be installed in the combustion zone of a hazardous waste incinerator will be exposed to a more severe temperature environment if utilized in conjunction with a rotary kiln or liquid injection unit. Specific flue gas parameters that may be found in each of the three principal incinerator types will be more fully discussed in Section 5 of this report.

TABLE 5. FLUIDIZED BED INCINERATION ADVANTAGES AND DISADVANTAGES

Advantages

1. General applicability for the disposal of combustible hazardous solids, liquids, and gaseous wastes.
2. Simple design concept, requiring no moving parts in the combustion zone.
3. Compact design due to high heating rate per unit volume (100,000 to 200,000 Btu/hr-ft^3 (900,000 to 1,800,000 kg/cal/hr-m^3) which results in relatively low capital costs.
4. Relatively low gas temperatures and excess air requirements which tend to minimize nitrogen oxide formation and contribute to smaller, lower cost emission control systems.
5. Long incinerator life and low maintenance costs.
6. Large active surface area resulting from fluidizing action enhances the combustion efficiency.
7. Fluctuation in the feed rate and composition are easily tolerated due to the large quantities of heat stored in the bed.
8. Provides for rapid drying of high-moisture-content material, and combustion can take place in the bed.
9. Proper bed material selection suppresses acid gas formation; hence, reduced emission control requirements.
10. Provides considerable flexibility for shockload of waste; i.e., large quantities of waste being dumped in the bed at a single time.

Disadvantages

1. Difficult to remove residual materials from the bed.
2. Requires fluid bed preparation and maintenance.
3. Feed selection must avoid bed degradation caused by corrosion or reactions.
4. May require special operating procedures to avoid bed damage.
5. Operating costs are relatively high, particularly power costs.
6. Possible operating difficulties with materials high in moisture content.
7. Formation of eutectics is a serious problem.
8. Hazardous waste incineration practices have not been fully developed.
9. Not well suited for irregular, bulky wastes, tarry solids, or wastes with a fusible ash content.

TABLE 6. TYPICAL HAZARDOUS WASTE INCINERATOR OPERATING RANGES

Process	Temperature range °C (°F)	Residence time
Liquid injection	650 - 1750 (1200 - 3180)	0.5 - 2 seconds
Rotary kiln	800 - 1600 (1470 - 2900)	Liquids & gases - seconds Solids - hours
Fluidized bed	450 - 980 (840 - 1800)	Liquids & gases - seconds Solids - hours

SECTION 4

EMISSION CONTROL DEVICES

In addition to the combustion zone, two additional sites that may be used for the placement of continuous emission monitors are those located immediately before and after the air pollution control (APC) device. Monitoring at these locations will typically be conducted to:

- provide a determination of the control device pollutant removal efficiency, and
- provide a determination of facility compliance with applicable emission regulations.

As previously stated, the Federal (EPA) emission requirements for a hazardous waste incinerator include:[8]

- destruction and removal efficiency of 99.99 percent for each principal organic hazardous constituent designated in the incinerator's permit,
- removal of 99 percent of the hydrogen chloride from the exhaust gas if the hazardous waste feed contains more than 0.5 percent chlorine, and
- a particulate emission limitation of 180 milligrams per dry standard cubic meter (0.08 grains per dry standard cubic foot) when corrected for 12 percent CO_2.

Continuous emission monitoring and stack (post-APC device) testing will be used to determine compliance with these standards.

Typical operating parameters for the pre-APC and post-APC device monitoring locations are dependent upon the type of device(s) installed. The selection of these devices is in turn dependent on the applicable emission regulations (local, state, and federal), the physical and chemical characteristics of the hazardous waste stream being incinerated, the types and amounts of pollutants generated, and the expected pollutant removal efficiency of the APC devices. This section briefly discussed the principal APC devices currently in use, their principals of operation, and their advantages and disadvantages. This data will serve to provide background information for the typical operating conditions that will be discussed in the next section of this report.

Air pollution control for the hazardous waste incinerators described in the previous section can be categorized as being primarily for particulate or gaseous emission control, although each device will remove some of the other pollutant stream. The particulate emission control devices favored by the hazardous waste disposal industry (based on existing installations) can be limited to afterburners and venturi scrubbers, although select, individual facilities may utilize electrostatic precipitators or fabric filters. Inasmuch as afterburners are only used today with rotary kiln incinerators and the principles of operation of these control devices are similar to liquid injection incinerators, they need not be discussed in more detail here. The venturi scrubber, which removes both particulate and gaseous emissions will be addressed. Gaseous control devices to be reviewed include packed bed towers, spray towers and plate columns (also known as tray towers). In addition, many control devices are commonly preceded by a heat recovery or quench section. Therefore, the purpose and nature of this pre-treatment will be addressed first.

Flue gases will exit a hazardous waste incinerator at temperatures ranging from 800 to 1100°C (1470 to 2000°F).[9] Before these gases enter an APC device, some form of gas cooling is practiced in a majority of hazardous waste incineration facilities. This temperature reduction serves to lower the volume of gases which must be handled by the APC device, and thereby lowers the size of the device required. At the same time, the lower gas temperature allows the use of low temperature materials of construction rather than more expensive, high temperature alloys or refractory.[2]

Flue gas cooling is typically practiced in one of two principal ways. The most common method, according to a recent survey of hazardous waste incinerator manufacturers[16] is heat recovery. This technique utilizes a waste heat boiler or some similar device to transfer heat in the flue gases to a second medium, either water or air. This practice recovers valuable energy that can be utilized elsewhere in the process while simultaneously lowering the flue gas temperature. The amount of energy recovered is dependent upon the final flue gas temperature, which in turn is set by the APC device. If an electrostatic precipitator is used, the outlet temperature from the heat recovery section is usually maintained at approximately 290 to 310°C (550 to 600°F). If a fabric filter or a wet scrubber is used, then the outlet temperature may be closer to 150°C (300°F).[7]

In place of, or at times, in addition to heat recovery, water quenching is used to lower flue gas temperatures. For these devices, a simple water spray system is used to adiabatically cool the flue gas 50 to 150°C (120 to 300°F).[2] If the gas is cooled below 95°C (200°F), acid resistant construction materials such as fiber reinforced plastic (FRP) must be used to minimize corrosion.[22] Quenching of the gas stream, especially before a wet collection device, also serves to minimize the evaporative water losses that occur in the principal scrubbing device. Without quenching, evaporative water loss from caustic or lime solution can lead to particulate emissions of sodium or calcium salts.[2]

VENTURI SCRUBBERS

One of the most predominant air pollution control devices for hazardous waste incinerators is a venturi scrubber, also known as a gas atomized spray scrubber. This device and other scrubbers are shown schematically in Figure 7. A typical venturi scrubber contains a section of ductwork with a converging central section (throat). Liquid is introduced at the throat and is atomized by the movement of incinerator flue gas through the throat section. The atomization breaks the liquid into fine droplets which allows a larger surface area for particulate interception. It is the gas/liquid contact that permits removal of gaseous contaminants, while it is the collision of particulates in the flue gas and the water droplets which causes particulate removal.

Quenching of the gas stream prior to a venturi scrubber is optional, as the venturi may be used for this purpose. If the gas stream contains acid gases, such as HCl, SO_2 or NO_x, a caustic solution may be used in the venturi to effect acid gas removal. However, significant amounts of HCl can be removed by water alone. For these cases, the interior surface of the venturi is typically lined with a nonmetallic material such as fiberglass reinforced plastic (FRP), rubber, carbon graphite, teflon or kynar (polyvinylidene fluoride).[9] Venturi scrubbers are usually followed by some form of mist eliminator to remove coarse water and acid mist droplets from the effluent air stream. This mist eliminator may be a cyclonic separator or it may be one of the other gaseous pollutant removal devices which will subsequently be discussed. The waste stream applicability and relative advantages and disadvantages of a venturi scrubber can be briefly summarized as follows.[2]

Applicable Waste Streams

Suitable for particles, and fairly effective in removing noxious gases that are highly soluble (HCl, HF) or reactive with the scrubber solution (SO_2, NO_x, HCN).

Advantages

1. Simultaneous gas absorption and particulate removal
2. Suitable for high temperature, high moisture conditions
3. Particulate removal efficiency is high
4. Scaling not usually a problem

Disadvantages

1. Corrosion and erosion problems
2. Dust is collected wet and the wastewater will have to be treated

3. Moderate to high pressure drop; large amount of energy needed

4. Requires downstream mist eliminator

PACKED BED SCRUBBERS

Packed bed scrubbers are used with hazardous waste incinerators because of their high removal efficiency for gaseous emissions. With proper design, packed towers can meet or exceed the federal 99 percent removal criteria for hydrogen chloride. The nature of the design, however, does not allow for high particulate loadings, and the packed bed can become clogged if inlet particulate concentrations are high. A venturi scrubber is used for particulate control in cases where some form of gas stream conditioning prior to the packed bed is required.

The packed bed scrubber is a vessel filled with randomly oriented packing material such as saddles or rings, as shown in Figure 7. The scrubbing liquid is fed to the top of the vessel while the flue gas flows in either cocurrent, countercurrent, or cross flow direction. As the liquid flows through the bed, it wets the packing material and thus provides a surface area for particulate mass transfer with the flue gas. Differences among packed bed scrubbers include the flow mode, the packing material and the depth of packing. The flow mode is dependent upon the particular application, while the depth of packing determines the liquid/gas contact time and hence affects the removal efficiency. Packing material comes in a variety of shapes and types including rings, spiral rings and saddles. Packing materials are usually made of plastic; ceramic or some other acid corrosion resistant material.

Packed scrubbers are most commonly used with liquid injection incinerators because of the low particulate loading in the exhaust gas. When used in conjunction with a rotary kiln or fluidized bed incinerator, they are usually preceded by a venturi scrubber. The applicable waste streams and relative advantages and disadvantages of packed bed scrubbers are summarized below.[2]

Applicable Waste Streams

Most suitable for the removal of noxious gases in streams containing low or no particulate loading.

Advantages

1. High removal efficiency for gaseous and aerosol pollutants

2. Low to moderate pressure drop

3. Engineering principles controlling the performance of packed bed scrubbers are well developed and understood

4. Availability of corrosion resistant packings to withstand corrosive materials

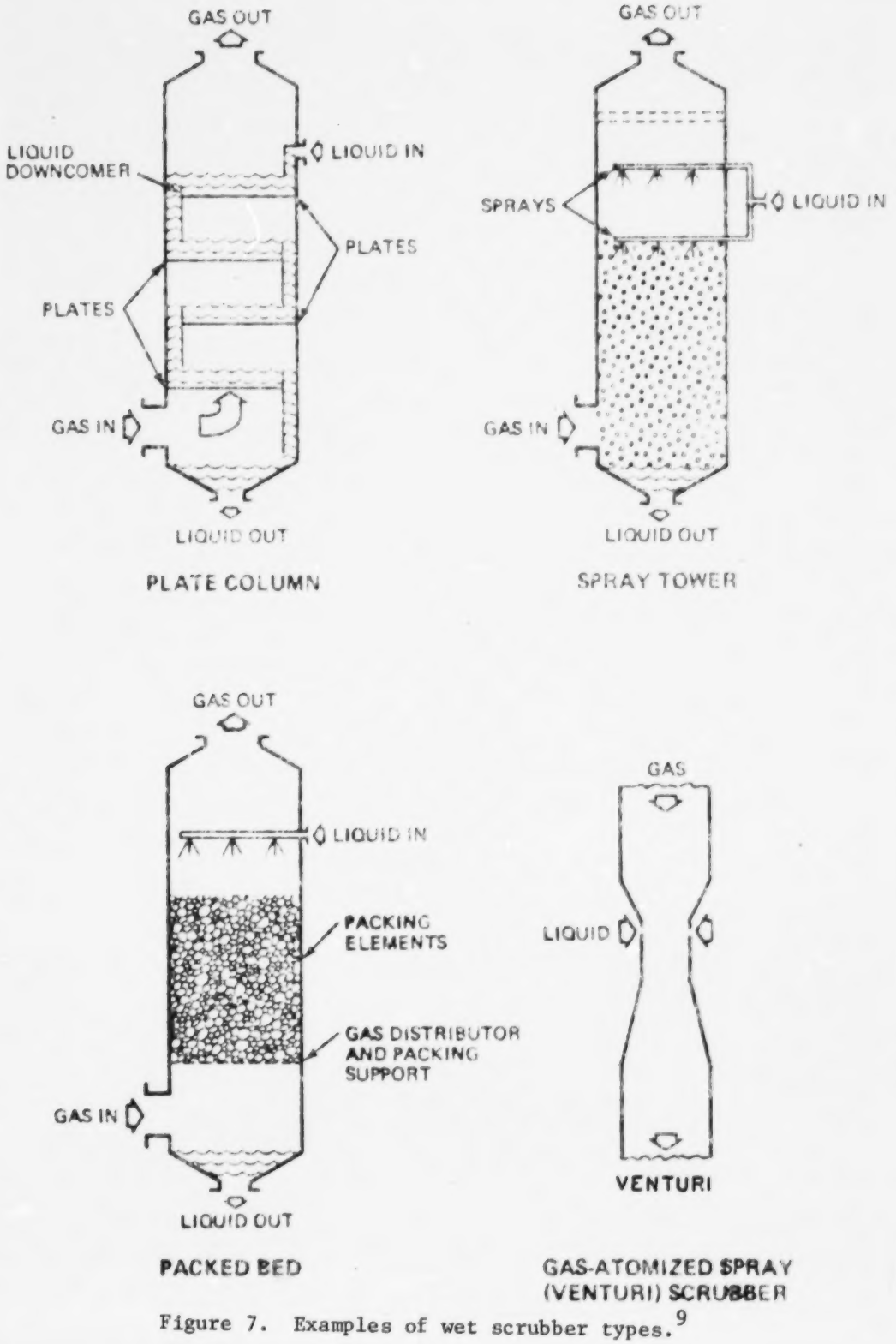

Figure 7. Examples of wet scrubber types.[9]

Disadvantages

1. Low removal efficiency for fine particles
2. Not suitable for high temperature or high dust loading applications
3. Requires downstream mist eliminator
4. Potential scaling and fouling problems
5. Possible damage to the scrubber if scrubber solution pumps fail.

SPRAY TOWERS

Preformed spray towers are scrubbers in which a scrubbing liquid is atomized by high pressure spray nozzles into small droplets and then directed into the flue gas stream within a confined chamber. This device is shown schematically in Figure 7. The waste gas stream usually enters the bottom of the chamber and flows countercurrent to the scrubbing liquid, although both cocurrent and cross-current modes have been used. As the scrubbing liquid becomes smaller, the relative surface area increases and gas absorption is enhanced. The gas/liquid interface may occur in a single path, or it may be directed by a series of baffle plates. In addition, the scrubbing liquid may be either water or a caustic solution to enhance gaseous pollutant capture. Inertial impaction of solid particles into the water is the principle particulate collection mechanism. It can be enhanced by operating with a high relative velocity between the gas and the liquid collection medium; however, very small particles do not have sufficient mass to enter a droplet. A summary of the waste streams amenable to spray towers and the relative advantages of this device follows.[2]

Applicable Waste Streams

Spray towers are suitable for gas streams with particles and gaseous pollutants.

Advantages

1. Simultaneous gas absorption and dust removal
2. Suitable for high temperature, high moisture, and high dust loading applications
3. Simple design
4. Rarely have problems with scaling

Disadvantages

1. High efficiency may require high pump discharge pressures
2. Dust is collected wet

3. Nozzles are susceptible to plugging

4. Requires downstream mist eliminator

5. Structure is large and bulky

6. Lower particulate collection efficiency than a high pressure venturi

7. Lower absorption efficiency than a packed tower

PLATE SCRUBBERS

Plate scrubbers are verticle cylindrical columns with a number of plates or trays inside as shown in Figure 7. Like all wet scrubbers, they utilize intimate gas/liquid contact to remove gaseous contaminants. Each plate has openings in the form of perforations or slots. The scrubbing liquid is introduced at the top plate and flows across it, then down to the next plate. A downcomer, located on alternate sides of each successive plate permits the downward flow of the liquid. The scrubbing liquid exits through an outlet located at the bottom of the unit. Incinerator gases enter the bottom of the tower and pass up through the plate openings before exiting at the top. The gas must have enough velocity to prevent the liquid from flowing through the holes in the plates. Gas absorption is promoted by the breaking up of the gas phase into little bubbles which pass through the volume of liquid in each plate. Plate towers with two sieve trays are often used as an absorber/mist eliminator in conjunction with a high energy venturi scrubber at many hazardous waste incineration facilities.[2] The applicable waste stream and relative advantages and disadvantages of these units are presented below.[2]

Applicable Waste Streams

Most suitable for the removal of noxious gases with low particulate loading.

Advantages

1. Simultaneous gas absorption and dust removal

2. High removal efficiency for gaseous and aerosol pollutants

3. Low to moderate pressure drop

4. Efficiency increases with multiple plates

5. Handles high liquid rates

Disadvantages

1. Low efficiency for fine particles

2. Not suitable for high temperature or high dust loading applications

3. Requires downstream mist eliminator

4. Limestone scrubbing solution causes scaling

5. Not suitable for foamy scrubbing liquid

The choice of scrubber types for gaseous emission control is principally determined by the contaminants to be controlled, the degree of emission reduction required and the particulate loading in the polluted gas stream. Where particulates are a significant problem, a venturi scrubber is typically used upstream of one of the other principal gas collection devices. At most hazardous waste incineration facilities, HCl is the principal gaseous contaminant requiring control. Waste streams containing other organic compounds are generated in much smaller quantities and are sometimes handled in special dedicated facilities.[9] In addition, scrubbers designed to control HCl emissions are generally also effective in reducing other acidic gaseous contaminants.

Plate towers, packed beds and gas atomized spray scrubbers (such as the venturi scrubber) are all suitable for the removal of 99 percent of the halogens from incinerator exhaust gas as well as for the control of P_2O_5 and SO_2 emissions. Preformed spray scrubbers are not capable of attaining this high level of control for gaseous contaminants, although these devices are more effective for particulate control.

The relative advantages and disadvantages of each air pollution control device result makes the applicability of any device site specific. For example, plate towers, packed beds and gas atomized spray scrubbers can all be used to control gaseous emissions from liquid injection incineration. Because of lower operating costs associated with lower pressure drops, the packed bed scrubber is the choice at most liquid injection facilities.[9] Packed beds and plate towers are generally more effective than gas to atomized spray scrubbers in reducing gaseous emissions, but less effective in controlling acid mists. In addition, plate towers or packed beds, when used in conjunction with gas atomized spray scrubbers, serve the dual function of eliminating the entrainment of liquid droplets while further reducing gaseous pollutant emission levels.

The comparative differences between the various scrubber types can be summarized as follows.[9]

- For incinerator effluent gases containing corrosive contaminants, the packed bed scrubber is simpler to construct than the plate tower built of acid to resisting alloy material. Also, the packing material can be readily changed to handle different kinds of corrosive fluids.

- The depth of packing in packed beds can also be changed if removal efficiency is lower than anticipated or if the carrier gas flow rate or waste streams incinerated change. There is usually no flexibility in increasing the number of plates in a plate tower.

- Unless operated at very high liquid rates, the pressure drop in packed bed scrubbers can be considerably lower than in plate towers designed for the same efficiency.

- For scrubbers less than about 1 to 1.5 meters in diameter, investment cost for packed beds are usually lower than for plate towers. When the scale of operation is large, however, plate towers are considered more economical.

- Plate towers are less susceptible to clogging problems and can be cleaned of accumulated particles and dusts more easily.

- Serious channeling problems of gas and liquid streams are not encountered in plate towers.

Based on each hazardous waste incineration facilities' specific waste feed composition and applicable emission limitations, an air pollution control system is designed. These systems, while containing different components, will typically have a particulate control device followed by some form of liquid scrubber for gaseous emissions. Prior to entering the initial control device, the flue gas stream is typically cooled to 50 to 150°C (120 to 300°F) by either direct water quench or some form of heat recovery. Exiting the last control device, the flue gases are emitted at approximately 70°C (160°F) and are saturated with water. While these approximations are site specific, they enable us to generalize continuous emission monitoring test conditions.

SECTION 5

OPERATING CONDITIONS

The specific operating conditions of interest with respect to continuous emission monitors include the temperature, pressure, moisture content, excess air level, and carbon dioxide, oxygen, and carbon monoxide concentrations of the gas stream as well as the concentrations of three principal air contaminants; sulfur dioxide (SO_2), hydrogen chloride (HCl) and nitrogen oxides (NO_x). A range of values for each of these parameters will be given for the three incinerator types under review and for the three monitoring zones of interest. These ranges will be based on engineering evaluations of the process under consideration and the types and compositions of hazardous wastes that may be burned in each incinerator. Where possible, published test data are included to provide actual test measurements as well as a comparison of how any parameter measurement might vary in a given test. Unfortunately in certain cases, such as the pre-air pollution control device zone, there are no published test results and only engineering estimates can be given. In other cases, such as combustion zone monitoring, the few test results that are available have been obtained during the incineration of hard-to-incinerate wastes such as PCBs and herbicide orange. The operating parameters recorded during these tests may be more severe than, and not necessarily representative of, typical hazardous waste incineration efforts. Nevertheless, where data was available, it was reported.

The reported monitoring parameter ranges are intended to provide a minimum and maximum for expected gas conditions. They should include most, but not necessarily all conditions that may be experienced in a hazardous waste burn. Individual incinerator operators may decide to operate at higher temperatures or at greater excess air rates than here presented to ensure complete destruction of the waste being incinerated. These situations were not prejudged in the establishment of a range for each parameter. In like fashion, the range of pollutant concentrations may be exceeded if a relatively pure stream of a single pollutant compound; i.e. hydrogen sulfide, is incinerated. Again it was judged that such an event is unlikely, and therefore should not be used to define an unreasonably high maximum concentration. With this background in mind, we can proceed to define specific hazardous waste incinerator monitoring conditions, starting with the combustion zone.

COMBUSTION ZONE

Liquid Injection

The combustion zone characteristics of a liquid injection incinerator can be the most extreme of the three types of incinerators studied. This can be attributed to the simple design which permits high temperature operation and their use in destroying a wide variety of hard-to-incinerate chlorinated organics, including pesticides and PCBs. These compounds require high temperatures for destruction efficiencies in excess of 99.99%. The specific operating temperature is set by the hardest to destroy or the most hazardous waste(s) to be incinerated and, as shown in Table 7, may vary from 650 to 1750°C (1200 to 3180°F). This temperature would be measured within the combustion zone, but not directly in the flame. Flame temperatures can be several hundred degrees centigrade higher than other combustion zone flue gas temperatures.[23]

The operating pressure within the combustion zone is determined by whether a forced draft and/or an induced draft fan is used to move combustion air and flue gases. If only a forced draft fan is utilized, the chamber will be under a few inches of positive pressure. Negative pressures are encountered at installations with induced draft fans. According to a recent survey of hazardous waste incinerator manufacturers, about half the vendors supply liquid injection units which operate under slight vacuum while the other half operates at a slight positive pressure.[16]

Combustion air flow rates for liquid injection incinerators range from 20 to 60 percent in excess of stoichiometric air requirements.[2,16] Ideally, incinerator operators attempt to minimize the amount of excess air while ensuring complete waste destruction as there is a decrease in thermal efficiency with increased excess air rates. In certain cases, however, thermal efficiency (and economic) considerations are secondary. In order to guarantee thorough waste/oxygen mixing while minimizing the potential for generating incomplete combustion by-products, incinerators may be operated at higher excess air levels. The incineration of herbicide orange cited in Table 7 is one such example. Since this chemical can potentially form extremely toxic dioxins if not completely combusted, it was incinerated with higher than normal excess air levels in the two liquid injection incinerators on board the incinerator ship, Vulcanus. This approach appeared successful since during the test series, no dioxins were detected in the combustion zone.[23]

Excess air levels are also directly related to both oxygen and carbon dioxide concentrations in the combustion gas. If there were no excess air, and all available oxygen was consumed in waste incineration, then the oxygen level would be zero and the carbon dioxide level would be a maximum. However, the introduction of excess air ensures that there will be a measureable amount of oxygen and that the carbon dioxide concentration of the combustion gas will be diluted. This inverse relationship between oxygen and carbon dioxide for various excess air levels is shown in Figure 8 for conventional fuels. The exact relationship for a hazardous waste is dependent upon the hydrogen,

TABLE 7. COMBUSTION ZONE MONITORING PARAMETERS

Incinerator type	Waste burned	Monitoring zone		Temperature °C	Temperature °F	Pressure in. w.g.	Excess air %	O_2 %	CO_2 %	CO ppm	H_2O %	SO_2 ppm	HCl %	NO_x ppm	References
Liquid Injection			Range	650-1750	1200-3180	-4 to 10	20-60	4-9	8-16	0-500	5-20	0-5000	0-7	0-5000	2,9,16
Test Data															
	#2 oil							6.3	9.8	12	10.9	15-20	—	170	18
	Ethylene			1349-1752	2460-3200			4.9-9.4	9.3-11.5	17-22	7.9-9.4	100-200	—	150-520	18
	C 5,6			1348-1378	2460-2510			5.5-8.1	8.4-9.7	17-20	12.7-14.7	5-6	1.15-2.35	120-145	18
	Herbicide orange	Wall flame		1115-1240	2040-2260		45-144	5.4-12.8	6.7-15.1	1-30			1.6-2.7		23
	Organo chlorine			1355-1566	2470-2850										
				1340-1500	2460-2730			9.0-11.3		25-75			4.0-6.2		26
Rotary Kiln		Kiln	Range	260-1260	500-2300	-.5 to 2.0	100-210	9-12	4-10	0-100	3-15	0-1500	0-2	0-2000	2,16
		Afterburner		870-1540	1600-2800		80-180								
Test Data															
	PVC	Kiln		870	1600		75-140	11.0-11.4	6.1-7.0	14-20			0.099-0.11	24-74	18
		Afterburner		980-1095	1800-2000										
	PCB	Kiln		Not operated				9.4-10	6.7-7.3	7-8			0.4	50-170	18
		Afterburner		1307-1332	2380-2430										
	Kepone			1038-1093	1900-2000										2
	PCB	Kiln		737-871	1359-1600										2
		Afterburner		1262-1321	2304-2410										
	PCB	Kiln		1252-1339	2236-2442										2
	Capacitors	Afterburner		1331-1332	2428-2430										
Fluidized Bed		Bed	Range	450-810	840-1490	-2.0 to 1.0	10-50	2-6	10-17	0-100	5-25	0-1000	0-1	0-1500	2,9,16
		Freeboard		600-980	1110-1800										
Test Data															
	Phenol	Bed		740-757	1360-1390			10.7-12.6	7.6-9.4	25 max				55 max	18
		Freeboard		813-899	1490-1650										
	Methyl	Bed		774-788	1420-1450			11.6-13.4							18
	Methacrylate	Freeboard		824-843	1510-1550										
	Volatile organics	Freeboard		1115	2042		105								21
	Chlorinated solvents	Freeboard		1115	2038		144								21

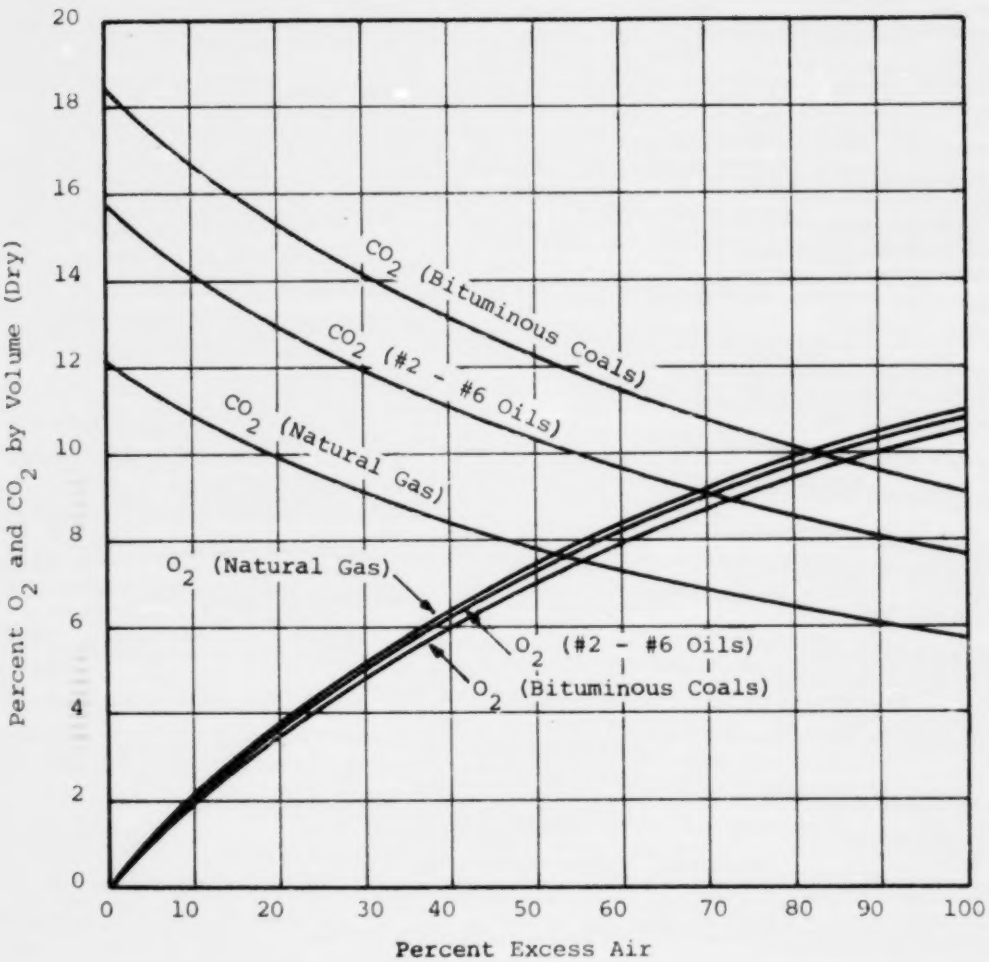

Figure 8. Relationship between boiler excess air and stack gas concentrations of excess oxygen (O_2) and carbon dioxide (CO_2) for typical fuel compositions.[24]

oxygen, carbon, and sulfur content of the waste, and will be similar to the fuel curves presented in Figure 8. The range of oxygen concentrations for liquid injection incinerators is from 4 to 9 percent, while the range for carbon dioxide is from 8 to 16 percent.

The carbon monoxide levels within the combustion zone are a function of the degree of combustion of the waste. Without intimate waste/air mixing, some of the carbon contained in the waste feed may escape the combustion zone without being completely oxidized. This condition is more likely if the fuel is not completely atomized, if the excess air level is too low or if the turbulence that creates waste/air mixing is insufficient. Based on published test data, carbon monoxide concentrations do not typically exceed 75 parts per million (ppm). Yet, data from a series of experimental destruction tests conducted on a range of pesticides indicates that carbon monoxide concentrations in the several hundred parts per million range are not uncommon and that peak values may reach several thousand ppm.[25] While this experimental incinerator was not a liquid injection unit, it was well designed, as pesticide destruction efficiencies in all tests did exceed 99.99 percent. This appears to indicate that high carbon monoxide levels are possible and that the specific CO level is somewhat dependent upon where the samples are taken from in the combustion chamber. Localized zones of relatively high CO levels may be present in a combustion chamber even if the waste is essentially totally combusted. Due to the short gas residence times of a liquid injection unit, these "hot spots" may occur and carbon monoxide may be channeled out of the combustion chamber. An engineering estimate on combustion zone carbon monoxide levels that may be encountered would therefore range from zero to 500 ppm. Based on actual liquid injection incinerator combustion zone monitoring data, however, CO levels below 100 ppm are more likely.

The moisture content of the combustion gases is highly dependent upon the moisture level of the waste being fired, and to a lesser extent on the relative humidity of the combustion air and the water vapor formed during waste combustion. The practice of incinerating a waste stream with a high (50 percent) moisture content is not economically attractive due to the high cost of auxilliary fuel and the inherent inefficiency of heating and vaporizing water. Yet it may be the easiest way to dispose of a wastewater stream contaminated with organics, and is therefore not uncommon. The moisture level within a combustion zone can vary considerably and levels measured during actual tests vary from 8 to 15 percent, as indicated in Table 7 none of these wastes contained a high moisture content, it is estimated that moisture levels may be higher, and an expectable range would be 5 to 20 percent.

Sulfur dioxide and hydrogen chloride concentrations within the combustion zone are also dependent upon individual facility firing practices. For example, as a worst case, if the incinerator is used to incinerate only those Appendix VIII substances with the maximum sulfur or chlorine concentrations (hydrogen sulfide--94 percent S, hexachloroethane--89.6 percent Cl) and no excess air is used, then the combustion gases could contain up to 26 percent SO_2 or up to 16 percent HCl. These values would be theoretical maximum

concentrations. Realistically, no incinerator would be operated without some level of excess air and this would serve to dilute these concentrations. Furthermore, hazardous waste incinerators would be expected to burn a mixture of wastes, and the composition of the mixture would not be expected to approach theoretical maximums, especially in the case of sulfur. The limited amount of test data reported in Table 7 for these pollutants indicates measured SO_2 levels up to 200 parts per million and hydrogen chloride levels slightly in excess of 6 percent. Yet, these levels would seem to understate the actual potential for SO_2 and HCl emissions. The problem with setting realistic ranges for both SO_2 and HCl combustion zone concentrations is determining what is representative. What combination of wastes will be incinerated together, and based on their chemical composition, what are the expected combustion zone SO_2 and HCl levels? One insight into realistic sulfur containing wastes that may require incineration is the aforementioned study done on pesticide disposal.[25] One of the pesticides incinerated in this study was malathion, with a sulfur content of 19.4 percent. This substance was diluted with solvent and burned at an effective (mixed) sulfur concentration of 11 percent. The resulting combustion zone SO_2 concentration was in excess of 3000 ppm. Allowing for the fact that 90 percent of the Appendix VIII sulfur containing compounds have a sulfur content less than 50 percent by weight, and that when incinerated, the sulfur content of their mixture would be less than half of their pure substance concentrations, it is estimated that the maximum sulfur content of a waste, as fired (including the dilution affects of auxiliary fuel) would be approximately 20 to 25 percent. Therefore, the estimated maximum combustion zone sulfur dioxide concentration range will be 0 to 5000 ppm. Should a compound with an extremely high sulfur composition such as H_2S or carbon disulfide (CS_2--84 percent S) be burned in a relatively pure state, then higher SO_2 concentrations will occur. This possibility is assumed to be remote.

Similarly, the likelihood that the maximum chlorine content waste (hexachloroethane) will be burned in a pure state is also remote. The organochlorine waste cited in Table 7 has a chlorine content of approximately 63 percent, and resulted in a HCl level of 6.2 percent in the combustion gas.[26] If a waste with a higher concentration of chlorine is burned, then higher combustion gas HCl would result, but auxiliary fuel would be required to support combustion, and the products of fuel combustion would tend to dilute the HCl concentration. These factors should balance each other out, and the resulting flue gas HCl concentration would be about the same. For this reason, it is estimated that the practical range of HCl concentrations is 0-7 percent.

Nitrogen formation is dependent upon both incinerator operating temperature (thermal NO_x) and waste nitrogen content (fuel NO_x). As liquid injection incinerators can operate at higher temperatures than the other two incinerator designs, these units will emit more thermal NO_x. Data taken during liquid incinerator tests to date report combustion zone NO_x emissions in the 500 ppm range. This is primarily thermal NO_x since the wastes contained little bound nitrogen. Combustion zone NO_x concentrations reported during the incineration of a pesticide that did not contain nitrogen

exceeded 1300 ppm,[25] so this level is perhaps closer to the maximum thermal NO_x concentrations that might be expected. However, the major unknown in estimating total NO_x from an incinerator is the contribution of fuel NO_x. Appendix VIII wastes can contain up to 85 percent bound nitrogen. Incinerators burning wastes with high nitrogen contents have emitted NO_x in the 5000 to 10,000 ppm range, according to one incinerator manufacturer.[27] Yet, if the NO_x levels become extreme, many incinerator operators will install a reduction furnace before or after the incinerator combustion zone to minimize NO_x emissions. There appears to be no set NO_x level where a reduction furnace is mandatory.[27] Each incinerator installation is designed to meet customer specifications which are, in turn, set by local air quality regulations. Taking this wide variety of factors into account, combustion zone NO_x levels are estimated to vary from 0 to 5000 ppm, with most incinerators emitting less than 1500 ppm.

Rotary Kiln

The reactions within a rotary kiln incinerator are less severe than those of a liquid injection combustion chamber. Temperatures and pressures are generally lower, and the excess air level and average gas residence times are higher, leading to a more oxidizing environment and a diluted pollutant stream.

Typical combustion zone temperatures within the kiln can range from 260 to 1260°C (500 to 2300°F) as shown in Table 7. This wide temperature range reflects the versatility of a rotary kiln in accepting and destroying at ideal temperatures liquids, solids, and sludges. Since most rotary kiln hazardous waste incinerators are operated with an afterburner to destroy residual organics, it is important to note these temperatures as well. Afterburners are typically operated at temperatures ranging from 870 to 1540°C (1600 to 2800°F).[2] The limited test data available on rotary kiln burns indicates that the incinerator can be operated at whatever temperature is required to destroy the waste fired, and that, as in the case of the PCB burn, the kiln section may be bypassed and the waste fired directly into the afterburner if this is compatible with system design.

Rotary kilns operate at a slight negative pressure.[16] The principal air movement equipment in these systems is an induced draft fan which is typically installed immediately before the stack and which causes the negative draft (-1.0 in w.g.) inside the kiln. Solids are fed into the kiln by gravity while liquids and sludges are injected under pressure. However, this pressure serves principally to atomize and disperse the wastes and is readily dissipated within the large volume of the kiln. When liquids are injected directly into the afterburner, this unit may operate at a slight pressure, much like a liquid injection incinerator. This condition is site, as well as burn, specific.

There is a wide variation in air volumes used in the operation of rotary kilns.[18] Some kilns are operated in a starved air mode (50 to 100 percent of stoichiometric air). Others are operated with up to 150 percent of excess air (250 percent of stoichiometric). This demonstrates some of the versatility of these units. Since rotary kilns burning hazardous wastes are always operated with an oxidizing secondary combustion chamber (afterburner), the net result is an overall excess air usage of 50 to 200 percent. A recent survey of hazardous waste incinerators[16] showed that the smaller rotary kilns (5 to 20 million Btu/hr) may or may not operate under starved air conditions, but the larger units nearly always operate with excess air in the kiln. Since it is usually desirable to maintain the afterburner at a higher temperature than the kiln, and because only liquid wastes or auxiliary fuel is fired in the afterburner, the excess air rate in this device can usually be controlled to less than that in the kiln. Rotary kiln excess air rates will typically vary from 100 to 210 percent while those maintained in the afterburner will range from 80 to 180 percent.[2]

The higher excess air rates in a rotary kiln versus a liquid injection incinerator result in higher kiln oxygen levels and lower carbon dioxide concentration in the combustion zone. Based on the standard excess air/oxygen/carbon dioxide relationships presented in Figure 8, rotary kiln oxygen levels can be estimated to vary from 9 to 12 percent, while carbon dioxide concentrations will range from 4 to 10 percent. Monitoring data taken from actual rotary kiln test burns confirms these ranges.

The higher excess air level and longer residence time of rotary kilns also serves to minimize the carbon monoxide concentration within the combustion zone of these units. Carbon from both the waste and any auxiliary fuel used is exposed for a longer time to an atmosphere which is richer in oxygen. This enhanced oxygen environment promotes the reaction to carbon dioxide at the expense of unburnt carbon and carbon monoxide and minimizes carbon monoxide levels. An engineering estimate of actual carbon monoxide levels within the combustion zone would be 0 to 100 parts per million.

The moisture levels within a rotary kiln combustion zone are like those of the liquid injection unit, dependent primarily on the moisture level of the feed. Identical wastes fired into either incinerator would result in identical moisture levels. However, the increased excess air level of the rotary kiln would generally tend to dilute these levels. The specific affect of this increased excess air depends upon its moisture content. Excess air at 20°C (68°F) and 50 percent relative humidity would contain only 1 percent (by weight) water, while the same air at 50°C (122°F) and 50 percent relative humidity would contain over 4 percent moisture. Higher temperature combustion air with a high relative humidity will lend a proportionally greater amount to total moisture levels, but will never outweigh the affect of a high moisture content waste. An engineering estimate of typical moisture levels within the rotary kiln would therefore be from 3 to 15 percent.

Since sulfur dioxide and hydrogen chloride concentrations are dependent upon the composition of the waste, their formation is not affected, per se, by

the type of incinerator used. However, once formed, these pollutants will be diluted by the excess combustion air present. As rotary kilns operate with 3 to 5 times the excess air levels of liquid injection units, we can conclude that pollutant concentration estimates developed for these units can be diluted by a comparable factor. Therefore, an engineering estimate of sulfur dioxide levels would be 0 to 1500 ppm and one for hydrogen chloride would be 0 to 2 percent. There is little or no actual combustion zone monitoring data available to substantiate these estimates. Should the rotary kiln be used in the starved air mode, as previously mentioned, then these estimates would hold true only for the afterburner section.

Nitrogen oxide formation is less severe with rotary kiln incinerators than with liquid injection units. Although the rotary kiln operates at a higher excess air rate and therefore has a greater amount of oxygen available for NO_x production than the liquid injection incinerator, it generally operates at a lower temperature and this is the controlling factor. As discussed earlier, the incinerator operating temperature is the principal variable in thermal NO_x production and peak operating temperature of only a few hundred degrees can produce a noticeable affect on NO_x emissions. Fuel NO_x production from rotary kilns should be comparable to that of liquid injection units, and may predominate if high nitrogen containing wastes are burned. It appears that the most important parameters in determining fuel bound nitrogen conversion appears to be the local conditions prevailing when the nitrogen is evolved from the fuel. Under fuel to rich conditions, this nitrogen tends to form N_2, whereas under fuel to lean conditions, significant amounts of NO_x are formed.[28] It is difficult, however, to quantify the affect of this phenomena on NO_x generation in the various incinerators reviewed in this report. The few tests to date which have measured combustion zone NO_x levels in rotary kilns demonstrate lower levels than similar data from liquid injection incinerators. An engineering estimate of the maximum range of NO_x levels that may be experienced in this zone is 0 to 2000 ppm, with typical levels below 1000 ppm.

Fluidized Bed

Fluidized bed incinerators operate with the least severe conditions of any of the three types investigated. The temperature, pressure and pollutant concentration levels within the combustion zone of these units are lower than the other incinerator designs. However, there is limited data available on combustion zone characteristics of fluidized bed incinerators when burning hazardous wastes and the available test data at times contradicts published design information. A review of combustion zone operating parameters for these units should keep in mind the ambiguity of available data.

Two combustion zone temperatures are generally referred to with respect to fluidized bed incinerators: bed and freeboard. Bed temperatures refer to the temperature within the bed of granular material where the waste is introduced. Bed temperatures are generally in the range of 450 to 810°C (840 to 1490°F).[2] The freeboard zone is the area directly above the bed where the hot combustion gases separate from the bed material. Combustion of wastes

is completed in this zone and temperatures are higher than bed temperatures, typically ranging from 600 to 980°C (1110 to 1800°F).[2] As noted in Table 7, testing has been conducted on a fluidized bed unit which was operated at temperatures in excess of this range. While uncommon in its high temperature and excess air levels, this test series serves to emphasize that the typical parameter ranges stated in Table 7 are not absolute ranges and may in certain situations be exceeded.

The pressure within a fluidized bed unit will vary, depending on where the measurement is taken, since both forced and induced draft fans are used. The waste being incinerated is usually injected into the bed under pressure. In addition, the fluidizing air which acts to suspend the bed material is also injected by forced draft fan into the bed under pressure. Consequently, there is a positive pressure within the bed itself. This pressure decreases as the air flows into the freeboard space above the bed, and the action of the induced draft fan dominates. The specific bed pressure and whether it is positive or negative therefore depends upon the monitoring location within the bed. A typical pressure reading could vary from +1.0 in. w.g. (in the bed)--2.0 in. w.g. (in the freeboard space).

There is somewhat of a contradiction in the literature concerning excess air rates for fluidized bed incinerators. Theoretically, these units can be run at low air levels, from 10 to 50 percent in excess of stoichiometric requirements.[16,17] In fact, one of the advantages of these incinerators is the low excess air requirements which minimizes the size and therefore the expense of the related air pollution control equipment. This relative advantage is contradicted by the data obtained from actual hazardous waste tests, as presented in Table 7. These data (two sets of tests conducted on each of two separate units) indicate excess air levels in the combustion zone exceeding 100 percent for each test series. The fluidized bed units for these tests were operated primarily to ensure complete (99.99 percent) destruction of the influent waste stream. Combustion air, far in excess of the amount required for complete waste destruction, was probably used as a precautionary measure and the economic penalties associated with handling and cleaning this larger volume airstream were accepted. For this analysis, we will assume that these higher excess air levels were atypical and that the actual levels that will be encountered in the field will be closer to the normal range of 10 to 50 percent.

This excess air rate assumption will also affect our estimates for oxygen and carbon dioxide levels in the combustion zone. Excess air levels of 10 to 50 percent translate to oxygen levels of between 2 and 8 percent and carbon dioxide concentrations ranging from 10 to 17 percent of the combustion gases. Should the fluidized bed unit be run with high excess air levels, as those for which test data is presented in Table 7, then the oxygen levels would approach 14 percent and the carbon dioxide levels 10 percent.

Regardless of the assumed excess air levels, carbon monoxide concentrations are low in the fluidized bed incinerator. The intense agitation of the bed material promotes turbulence and good mixing of waste and

fuel, thereby minimizing the formation of incomplete combustion products such as carbon monoxide. As is evident in Table 7, there is only one data point for fluidized bed combustion zone carbon monoxide level, which is a maximum concentration of 25 ppm. Allowing for the fact that the high excess air level for this test series may have depressed typical expected CO concentrations, it is estimated that a typical carbon monoxide range would be 0 to 100 ppm.

Moisture levels are affected by both the moisture content of the waste, the water vapor formed by the combustion of hydrogen, and the relative humidity of the combustion air. Since one of the advantages of the fluidized bed incinerator is its ability to handle high water content wastes such as sludges, it is expected that the moisture content of the incinerated waste could approach 80 to 90 percent. An engineering estimate of the range of expected flue gas moisture levels would therefore be 5 to 25 percent. No data on actual combustion zone moisture concentrations could be found in the literature.

Estimates of both sulfur dioxide and hydrogen chloride concentrations should be based, as before, on the maximum sulfur and chlorine concentrations of the Appendix VIII waste and the amount of dilution air attributable-excess air. Following this technique, the maximum SO_2 and HCl concentrations in the combustion zone of a fluidized bed incinerator should be higher than the other incinerators, since the normal excess air level is lower. However, there are other factors that would play a part, should these pollutant levels become excessive. Specifically, the bed material can be altered to allow for the adsorption of acid gases, by adding lime or some other caustic solid. Since this can be accomplished with only minor modifications to the system, and since adsorption of acid gases in the bed would reduce the need for further protection of incinerator internals downstream, such a practice would probably be adopted for wastes with high sulfur and/or chlorine contents in a fluidized bed incinerator. Based on this assumption, it is estimated that the range of sulfur dioxide concentrations, as measured in the freeboard space, would be in the 0 to 1000 ppm range, and HCl levels would be 0 to 1 percent.

Nitrogen oxide concentrations in the combustion zone of a fluidized bed incinerator will be the lowest of any of the three incinerator designs reviewed. This is attributable to the relatively low temperature and low excess air level at which these units are operated. Only one of the test series conducted on fluidized bed units while burning hazardous wastes measured NO_x levels. This test reported a maximum concentration of 25 ppm. Based on currently available data, a best engineering judgement of combustion zone NO_x concentrations is 0 to 1500 ppm. This range assumes that the thermal NO_x level is much less than the other incinerator designs and that when a high nitrogen content hazardous waste is burned, the contribution of fuel NO_x is comparable.

PRE-APC DEVICE MONITORING LOCATION

Monitoring hazardous waste combustion flue gas parameters before an air pollution control device has not been reported in the literature. The principal purpose of such monitoring would be to verify control device efficiency. Estimates of expected flue gas characteristics must therefore be made using best engineering judgement, based on combustion zone conditions and changes that may occur to the gas stream between the combustion zone and the air pollution control device.

As discussed in Section 3, some form of heat recovery or water quenching is usually practiced on the gaseous effluent of hazardous waste incinerators to reduce total flue gas volume. Therefore, as a point of reference, the pre-control device monitoring zone will be defined as being located after this cooling zone, and immediately preceeding the control device. This definition enables us to limit our analysis of monitoring parameters to the affects of flue gas cooling or conditioning. As will be shown, only a few flue gas parameters are changed when the temperature of the gas stream is lowered, and due to the similarity of flue gas cooling devices, these changes will be similar for the various types of incinerators. The various parameters and their ranges of values will be defined, again by incinerator type. All parameter estimates at the monitoring zone immediately before the air pollution control device (pre-APC device) are presented in Table 8.

Liquid Injection

A liquid injection incinerator will be followed by a heat recovery device or a quench section/conditioning tower depending on the magnitude and extent of pollutants generated. During waste incineration, if the gas stream is not excessively corrosive, a heat exchanger will be used to recover valuable energy, otherwise the gas stream will be simply cooled using water sprays. Heat recovery units, either heat exchangers or waste heat boilers, simply lower the temperature of the flue gases by transferring the heat to another medium, such as air (e.g. heat exchanger) or water (e.g. waste heat boiler). These units are commonly used when no appreciable amount of SO_2, NO_x, or HCl or other pollutants are generated that can potentially erode internal metal surfaces, or when the outlet temperature of the heat recovery device can be maintained above the condensation temperature of the acid gases, thereby limiting corrosion and erosion.

A quench or conditioning section utilizes the evaporation of water to lower the flue gas temperature and reduce the volume of flue gas that must be treated. Since the concentrations of gaseous constituents in the flue gas (O_2, CO_2, CO) and gaseous pollutants (SO_2, HCl, NO_x) are measured on a dry, water free basis, these concentrations will not be altered. However, it must be noted that the addition of water will add to the total mass of the flue gases and on an absolute basis, these concentrations will be altered. Since a continuous emission monitoring system will usually condition the gas stream (remove moisture) before measuring its components, the convention of stating gaseous concentrations on a dry basis will be retained. A quench

TABLE 8. PRE-AIR POLLUTION CONTROL DEVICE MONITORING PARAMETERS

Incinerator type	Cooling method	Temperature °C	Temperature °F	Pressure in. w.g.	Excess air %	O_2 %	CO_2 %	CO ppm	H_2O %	SO_2 ppm	HCl %	NO_x ppm
Liquid Injection	Heat recovery	150-315	300-600	-10 to 8	20-60	4-9	8-16	0-100	5-20	0-5000	0-7	0-5000
	Water quench	65-175	150-350	-4.5 to +9.9	20-60	4-9	8-16	0-100	40-60	0-5000	0-7	0-5000
Rotary Kiln	Heat recovery	150-315	300-600	-2.5 to -8.0	80-210	9-12	4-10	0-50	3-15	0-1500	0-2	0-2000
	Water quench	65-175	150-350	-0.6 to -2.5	80-120	9-12	4-10	0-50	40-50	0-1500	0-2	0-2000
Fluidized Bed	Heat recovery	150-315	300-600	-1.0 to -8.0	10-50	2-8	10-17	0-50	5-25	0-1000	0-1	0-1500
	Water quench	65-175	150-350	-2.5 to +0.9	10-50	2-8	10-17	0-50	40-65	0-1000	0-1	0-1500

section is typically used before a scrubber, when flue gas volume reduction is the prime concern. A conditioning tower also utilizes water to lower gas temperature, but the final gas temperature is higher and will vary depending on whether an electrostatic precipitator or a fabric filter is installed for particulate control. With this background in mind, we can examine specific flue gas parameters.

Due to design considerations, the flue gas temperature exiting a heat recovery device is usually limited to a minimum of approximately 150°C (300°F). This will be the typical temperature if a fabric filter or a scrubber follows heat recovery. If an electrostatic precipitator is the collection device in use, or if acid gas condensation is to be avoided, the typical heat recovery exit temperature is 315°C(600°F). A quench tower is almost always followed by a wet collection device, either an absorber for acid gas removal, or a venturi scrubber for combined particulate and gaseous pollutant cleaning. Quench tower exit temperatures will vary from 65 to 175°C (150 to 350°F), although if the lower temperature is reached, acid gases will begin to condense on internal surfaces and some form of corrosion protection must be employed. In certain cases where a venturi scrubber is utilized, no quenching is employed and the gas temperature at this monitoring location can approach 1090°C (2000°F).[29] These cases are somethat uncommon and have not been affected in the estimated average temperature range.

As noted in Table 8, the pressure of the combustion gases that exit the liquid injection incinerator can range from -4 to +10 inches, water gauge (in. w.g.). This pressure will become increasingly negative as the gases get closer to the inducted draft fan inlet. At the Pre-APC device monitoring location, the range of potential pressure can be estimated to equal the sum of the incinerator pressure, plus the pressure drop across the cooling section. Waste heat boilers have an estimated pressure drop of from 2 to 6 in. w.g., depending on the number of sets of tubes, the existence of an airheater, etc. When added to the furnace outlet pressure, this results in an estimated monitoring zone pressure from -10 to +8 inches, water gauge. Quench towers have a much lower pressure drop, from 0.1 to 0.5 in. w.g. Therefore, if these devices are used, the overall pressure at the monitoring zone may vary from -5 to +10 in. w.g. It must be emphasized that these estimates assume that the position of the fan is downstream of the air pollution control equipment, near the exhaust stack. If the fan is located between the incinerator and the cooling section or if multiple fans are used, then the aforementioned estimates may not hold true. The most common process flow arrangement is that which has an induced draft fan located immediately before the exhaust stack and is used to determine monitoring zone parameters for all values stated in this section.

Any changes in the excess air, oxygen and carbon dioxide concentrations of the flue gas at this monitoring location will occur if there are leaks in the ductwork and/or the cooling equipment. If the system is operated at a negative pressure in the cooling region, any leakage would cause an

infiltration of outside air into the flue gases and result in higher amounts of excess air and oxygen, and a lower carbon dioxide concentration. For this study, however, we will assume that the incinerator and its associated systems are rigorously inspected and maintained and that any noticeable deterioration of the system is immediately repaired. This assumption precludes the influx of ambient air and allows us to estimate that the excess air, oxygen and carbon dioxide percentages of the flue gas are identical to those at the combustion zone. Excess air would be in the 20 to 60 percent range, oxygen from 4 to 9 percent, and carbon dioxide from 8 to 16 percent.

Carbon monoxide (CO) concentrations will be lower in the Pre-APC device monitoring location than they will be in the combustion zone. Carbon monoxide destruction is related to both temperature and residence time, as shown in Figure 9. The longer CO is allowed to remain in high temperature oxidizing environments, such as that which is present in the flue gas exiting the incinerator, the lower will be the final CO concentration. While this elevated flue gas temperature is only maintained until the gases pass through the cooling sections, this additional residence time should be sufficient to lower CO concentrations appreciably. The extent of this reduction can only be estimated, and this engineering estimate would place CO concentrations at between 0 and 100 ppm, or a reduction of approximately 80 percent.

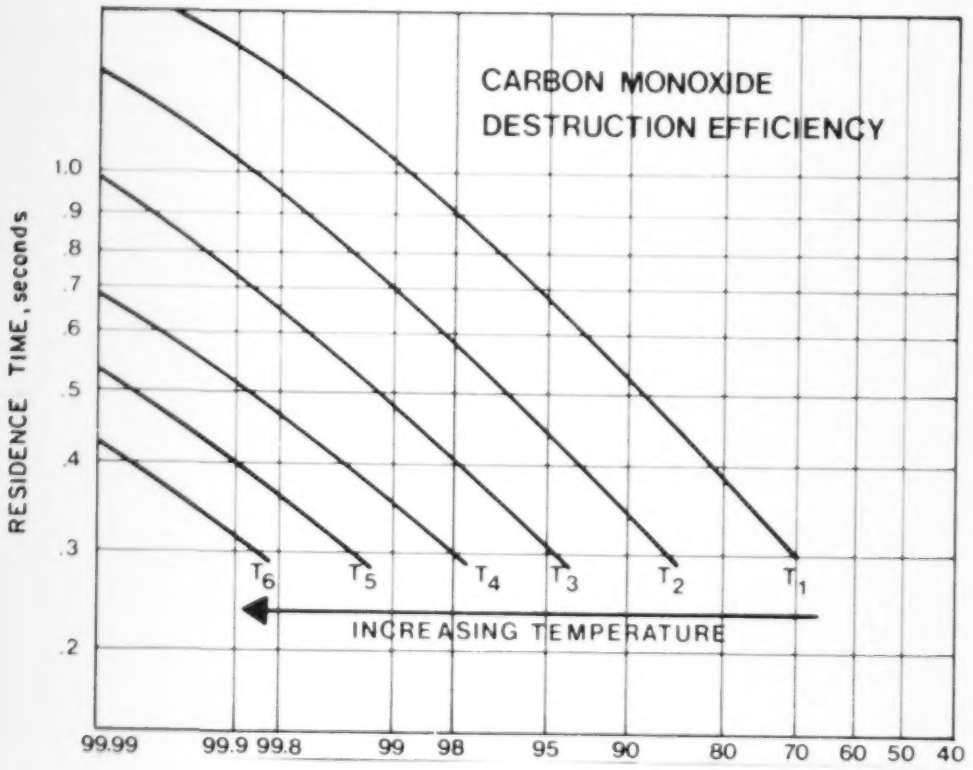

Figure 9. Carbon monoxide destruction efficiency.

The moisture content of the gases will of course be greatly influenced by the type of cooling device used. Waste heat boilers add no moisture to the gas stream, and the gas compositions of the flue gases after these devices is within 5 to 20 percent the same as that exiting the incinerator. Use of a quench chamber adds significant amounts of water to the gas stream. Depending on the temperature of the gases as they leave the quench section, from 35 to 40 percent of the volume of the total gas stream is water added in the quench chamber. When added to the moisture present in the waste, the total moisture content at this monitoring location is estimated to be 40 to 60 percent.

There will be no change in the sulfur dioxide, hydrogen chloride or nitrogen oxide concentration of the flue gases between the combustion zone and the Pre-APC device monitoring zone. While the temperature and therefore the volume of flue gases will be greatly reduced, the pollutant volumes will be reduced proportionately and therefore the pollutant concentrations will remain unchanged (assuming ppm levels of pollutants). Due to the lower temperature, there may be a change in the concentration of nitrogen dioxide since it is water soluble, but the overall NO_x concentrations will not be appreciably affected. Furthermore, it is assumed that if a quench section is used, only enough water is added to lower the temperature. Excess water added in the quench will serve to lower the flue gas below the dewpoint of these pollutants and will scrub some of the gaseous pollutants from solution, thereby reducing their concentrations. This is assumed not to happen since it would require that some method of removing and neutralizing these gases be provided in this section. Nonetheless, facility operators will often line their quench chambers with an acid resistant material to protect the internal surfaces should an operating problem occur that results in excess water addition and the subsequent condensation of acid gases.[22] If by design or accident, water is added in the quench chamber far in excess of what is needed to simply cool the gases, then the concentrations of SO_2, NO_x and especially HCl will be lower than those estimates in Table 8. These Table 8 figures therefore could be considered maximum values. The estimates established for the three gaseous pollutants at the combustion zone will be unaffected by cooling and will remain unchanged; 0 to 5000 ppm for SO_2, 0 to 7 percent for HCl and 0 to 5000 ppm for NO_x.

Rotary Kiln

An analysis identical to that for liquid injection incinerators was conducted for rotary kiln units. The parameter ranges presented for the combustion zone in Table 7 will serve as an initial set of conditions and the affects of cooling on these conditions will be discussed.

Flue gases exiting a rotary kiln will be treated similar to those from liquid injection incinerators; they will be cooled by means of a waste heat boiler or a quench chamber/conditioning system. Due to its versatility, a rotary kiln may be used for a wide range of waste types and compositions. Waste heat recovery is less likely to be practiced when the waste quantity and composition fluctuate widely, as might be expected in a diversified industrial complex.[30] Fluctuations affect the reliability of the heat recovered and thus the economics of this auxilliary system. When practiced, waste heat

recovery lowers the flue gas temperature to approximately 150 to 315°C (300 to 600°F) depending on the type of device utilized. A quench chamber can lower the temperatures even more, to the 65 to 175°C (150 to 350°F) range. As with liquid injection processes, the temperature at the Pre-APC device monitoring location depends upon the type of APC device installed, and this device depends on the type and amount of pollutants generated.

As stated earlier, the pressure drop across a waste heat recovery boiler may range from 2 to 6 in. w.g. and for a quench chamber from 0.1 to 0.5 in. w.g. When added to the slight negative pressure that exists at the rotary kiln outlet, the pressure at the Pre-APC device monitoring location will vary from -2.5 to -8.0 in. w.g. for waste heat applications from -0.6 to -2.5 in. w.g. for quench chamber installations.

As with liquid injection incinerators, rotary kilns are assumed to be air tight, with no leakage of ambient air into the flue gas stream. While maintaining a tight air seal at the incinerator end may be an operational problem for rotary kilns,[30] the potential air infiltration at this point has been accounted for in the high excess air rates estimated for these units under combustion zone conditions. The excess air rate, and oxygen and carbon dioxide levels, will be assumed identical to those at the combustion zone; 80 to 210 percent excess air, 9 to 12 percent oxygen, and 4 to 10 percent carbon dioxide.

The carbon monoxide concentration for rotary kilns is also estimated to be reduced due to the increased residence time at the high temperature oxidizing atmosphere the carbon monoxide will experience. Since the oxygen concentration is even greater with rotary kilns than it is for liquid injection incinerators, the reduction in carbon monoxide should be proportionately greater. Yet, as the CO concentration is lowered, oxidation of the residual amount remaining becomes more difficult. Therefore, it is estimated that the carbon monoxide concentration at this point is lower in rotary kilns than it is for liquid injection units, even if the percent reduction from the combustion zone to this monitoring site is not as great. An estimated CO range would be 0 to 50 ppm.

The moisture content of the flue gas will be dependent on whether heat recovery or water quenching is used to cool the gas stream. As with liquid injection incinerators, the flue gas from rotary kilns will maintain its moisture content if some form of dry cooling, such as heat recovery, is used. The combustion chamber moisture level of 3 to 15 percent would be maintained in these cases. If, however, water quenching is employed, then the flue gas stream moisture content will be raised by, 35 to 40 percent, or to a total of approximately 40 to 50 percent.

Concentrations of the specific pollutants of interest in this study, sulfur dioxide, hydrogen chloride and nitrogen oxides, are measured on a dry basis, and should not be affected by any increase in flue gas moisture content. As stated before, these pollutant levels would be affected if excessive water is added in the quench chamber and the flue gas temperature falls below the dew point of these compounds. But, we have assumed that this

does not occur and that the pollutant concentrations, on a dry basis, essentially remain the same as those in the combustion chamber; 0 to 1500 ppm for SO_2, 0 to 2 percent for HCl, and 0 to 2000 ppm for NO_x.

Fluidized Bed

The flow of combustion gases from a fluidized bed incinerator is similar to that from the other incinerator types. The gas stream is passed through either a heat recovery device or a water/quench conditioning section where the temperature is lowered to a level compatible with the air pollution control device into which the gas stream will flow. These final temperatures are identical to those previously described for the other incinerators; 150 to 315°C (300 to 600°F) for gases exiting a dry heat recovery device, and 65 to 175°C (150 to 350°F) for gases leaving a water quench. Again, the exact temperature will depend upon the type of air pollution control device installed.

The pressure of the gas stream also depends on whether a heat recovery device or a quench chamber is used. As discussed earlier, there is a wide range of possible pressure losses, depending on which type of cooling equipment is used. Quench chambers, which employ water sprays, have a low pressure drop, ranging from 0.1 to 0.5 in. w.g. Simple air to air heaters have a slightly higher pressure drop, some 1 to 3 in. w.g. while waste heat recovery boilers have the greatest loss of pressure, some 2 to 6 in. w.g. All fluidized bed units will utilize a blower or fan to supply combustion/ fluidizing air at the base of the bed, and a second fan, typically located immediately before the exhaust stack. The likelihood that this second fan will be located between the combustion zone and the air pollution control device is slight. Therefore, there is little likelihood that there will be an increase in gas pressure either before of after the cooling section. The pressure drop across the cooling device will serve to lower the existing combustion zone pressures. The estimated gas pressure at the pre-APC device monitoring zone location will range from -1.0 to -8.0 in. w.g. For installations with heat recovery devices to -2.5 to +0.9 in. w.g. for processes that utilize water quenching. The small relative difference in the range of gas pressures for fluidized bed units vis a vis the other incinerators is maintained at this monitoring location.

The discussion of excess air rates, and oxygen and carbon dioxide concentrations that was presented earlier for the other incinerators holds true for fluidized bed units as well. Assuming there are no leaks where ambient air can infiltrate and dilute the flue gases, the range of these parameters will remain unchanged at 10 to 50 percent excess air, 2 to 8 percent oxygen, and 10 to 17 percent carbon dioxide.

Carbon monoxide levels should be lower at this monitoring location due to the increased opportunity for further oxidation. Since the flue gas oxygen concentration for fluidized bed incinerators is lower than that for rotary kilns, the carbon monoxide reduction may not be as great. Yet, it is assumed that a minimal reduction of 50 percent does take place, and that the estimted range of carbon monoxide concentrations at this monitoring location will be 0 to 50 ppm.

Flue gas moisture levels are dependent on the addition, if any, of water in the cooling zone. For dry cooling devices, no moisture is added, and the combustion zone moisture content estimate of 5 to 25 percent is maintained. For quench chambers, an additional 35 to 40 percent, by volume, moisture is added, thereby raising the total moisture content to 40 to 65 percent.

Finally, without the addition of ambient air, the concentrations of sulfur dioxide, hydrogen chloride, and nitrogen oxides on a dry basis will be the same as for the combustion zone; 0 to 1000 ppm for SO_2, 0 to 1 percent for HCl, and 0 to 1500 ppm for NO_x.

POST APC DEVICE

The final monitoring zone of concern with respect to continuous emission monitoring parameters is the stack or post air pollution control device site. By the time hazardous waste incinerator effluent gases reaches this point, they will have been conditioned, cooled and cleaned. Final stack gas quality, from an air pollution standpoint, will be set by applicable Federal, state and lcoal air quality regulations. The federal regulations for hazardous waste incinerators were stated in Section 4. Since hazardous waste incineration is still an emerging technology, many state and local regulations have yet to establish regulations limiting stack emissions. As a result, a wide range of possible flue gas concentrations is possible. None-the-less an estimate of stack parameters can be stated, based on standard air pollution strategies. Once again, this analysis will proceed from the last monitoring zone, located before the APC device, to the stack site, and will quantify the effects of air cleaning on flue gas parameters. All flue gas parameter estimates are reported in Table 9.

Liquid Injection

As with the pre-APC device montoring zone, flue gases at the stack location can be generally categorized as being either "dry" or "wet." These designations refer not only to the method of flue gas cooling, but also to the type of air pollution control employed. Dry APC devices which include electrostatic precipitators (ESPs) and fabric filters will be used when particulates are the only emission of concern. Electrostatic precipitators will typically be operated in the 150 to 315°C (300 to 600°F) range while fabric filters have a practical upper operating limit of 145°C (290°F).[9] Both devices have a lower temperature limit that is set to avoid condensation of water or any acid gas in the flue gas on the internals of the device. In addition, fabric filters have the additional consideration of bag plugging due to condensation of organics, water and/or acid gases. While the specific minimum temperature is determined by the flue gas composition and the corresponding acid gas dew points, a practical minimum temperature is approximately 90°C (200°F). Allowing for a 10 percent loss in temperature between the air cleaning device and the stack, it is estimated that dry collection devices will have stack temperatures in the 80 to 280°C (175 to 535°F) range.

TABLE 9. POST APC DEVICE (STACK) MONITORING PARAMETERS

Incinerator type	Air pollution control	Stack temperature °C	Stack temperature °F	Pressure excess in. w.g.	Pressure excess Air (%)	O_2 %	CO_2 %	CO ppm	H_2O %	SO_2 ppm	HCl %	NO_x ppm
Liquid injection (range)	Dry	80-280	175-535	-2.0 to +2.0	40-80	6-10	7-11	0-100	5-20	0-4000	0-0.04	0-4000
	Wet	60-90	140-190	-2.0 to +2.0	40-80	6-10	6-10	0-100	20-63.5	0-800	0-0.056	0-4000
Rotary kiln (range)	Dry	80-280	175-535	-2.0 to +2.0	100-230	10-14	3-8	0-50	3-10	0-1200	0-0.04	0-1600
	Wet	60-90	140-190	-2.0 to +2.0	100-230	10-14	2-7	0-50	20-63.5	0-240	0-0.016	0-1600
Fluidized bed (range)	Dry	80-280	175-535	-2.0 to +2.0	30-70	5-9	8-12	0-50	5-25	0-800	0-0.04	0-1200
	Wet	60-90	140-190	-2.0 to +2.0	30-70	5-9	7-11	0-50	20-63.5	0-160	0-0.008	0-1200

Wet collection devices will have a much narrower temperature range. Regardless of the inlet temperature to the device, the maximum outlet temperature will be 100°C (212°F). The flue gas in this condition would be completely saturated with water and would most likely be vented through some form of mist eluminator to remove entrained water droplets. Temperatures as low as 65°C (150°F) have been reported at the scrubber outlet,[9] and this is a realistic lower limit for these devices. Again allowing for a 10 percent temperature reduction from the scrubber and/or mist eliminator, to the stack, the temperature range for wet collection devices would be 60 to 90°C (140 to 195°F).

The flue gas pressure at the stack monitoring location will depend on both the affects of the prime air movement fan and the natural draft and related negative pressure that occurs in a stack due to the stack height. Incinerator systems typically utilize an induced draft fan, located between the final APC device and the stack, to pull combustion gases through the entire system. This fan will discharge air into the stack with a slight positive pressure, typically 0 to 2 inches, water gauge. As the flue gas enters the stack this pressure dissipates, and the stack draft begins to predominate. Stack draft is a natural negative draft that occurs in the stack due to elevated temperature of the stack gases and the height of the stack. The stack draft will typically range from 0 to -2.0 in. w.g. The actual pressure of the flue gases will therefore depend on these two factors, and where the measurement is being taken. A positive pressure will be measured closer to the fan outlet while the pressure will be increasingly negative as the gases move up the stack and the natural draft affect takes over. A range of stack pressures, regardless of the type of air cleaning employed would therefore be -2.0 in. w.g. to +2.0 in. w.g.

The excess air rates and related oxygen and carbon dioxide concentrations at the stack monitoring location should not change dramatically from the pre-APC device site. This is attributable to restrictions in total system air flow which are established by the induced draft fan. Since the fan is designed for overall system air flow requirements, any substantial leakage of ambient air into the system will overload the fan. This condition will potentially lead to poor system performance in terms of lower pollutant collection efficiencies and should be noticed by changes in key process parameter indicators, such as pressure drop and temperature. Thus, while some air leakage before the fan is possible, extensive leakage is unlikely to be a long term problem. Air infiltration between the fan and the stack is more likely to account for such leakage. It is estimated that the total excess air rate will increase by approximately 20 percent, thereby changing the range for this parameter from 40 to 80 percent. No actual test data could be found to substantiate this estimate. In addition, it is recognized that individual facilities may have higher excess air rates, depending on operating and maintenance conditions. The corresponding range of oxygen concentrations for this excess air estimate will be approximately 6 to 10 percent, for both dry and wet APC devices. The range of carbon dioxide concentrations at the stack site will be different depending on whether a wet scrubber is used, and also depending on the alkali which is used in conjunction with the scrubber. Carbon

dioxide is, itself, an acid gas. It will react with alkaline solutions and, to a limited extent, be scrubbed from the flue gases. For example, the overall mass transfer rate for CO_2 removal in a sodium hydroxide scrubbing solution is as much as one third that of the more common acid gas, sulfur dioxide.[9] Due to the number of variables involved in calculating the exact CO_2 removal efficiency in a system, only a qualitative estimate can be made. It is projected that a standard CO_2 range for dry systems will be 7 to 11 percent, while the range for wet systems may be closer to 6 to 10 percent.

Carbon monoxide is assumed to be unchanged by either the dry or the wet collection devices. While some additional oxidation may occur, the relatively low temperature of the flue gas as it traverses the APC device does not favor significant conversion of CO to CO_2. Therefore, the estimated range for CO remains at 0 to 100 ppm.

The moisture content of the flue gases will depend on the type of APC device employed. For dry devices, no additional water is added and the estimated moisture content remains at 5 to 20 percent. For wet collection, an interesting phenomena can occur across the collection device; if the outlet temperature of the device is at the lower end of the range stated in Table 9, the moisture content of the flue gas may, in fact, decrease. This is attributable to the decreased ability of flue gases (and air) to retain moisture at lower temperatures. Flue gas which is saturated at 90°C (190°F) will contain 63.5 percent moisture. The same gas at 60°C (140°F) will contain only 20 percent moisture. These two saturation capacities will therefore define the maximum moisture content of the flue gases at the stack monitoring location. The scrubber, in cooling the stack gas also acts as a condenser in removing moisture from this gas. The resulting moisture levels (assuming saturation of the flue gas) at the temperatures stated in Table 9, will vary from 20 to 63.5 percent.

Estimation of stack gas acid gas levels is another area where there are a number of indeterminate variables, each of which can affect concentration estimates. The first of these variables is applicable regulation. The Federal Regulation for hydrogen chloride is clear; 99 percent removal. Applying this removal efficiency to the maximum estimated HCl content given in Table 8, we can estimate a stack gas HCl range of from 0 to 700 ppm (0 to 0.07 percent). Due to the high degree of solubility of HCl in water, removal efficiencies in excess of 99 percent have been reported for scrubbers utilizing water alone. Scrubbers employing a caustic solution have reported collection efficiencies as high as 99.9 percent.[9] For dry collection systems, the maximum hydrogen chloride content is set by the corrosion resistance of the equipment. For example, HCl concentrations into ESPs are kept below 1000 ppm and usually average 300 ppm.[9] When the 20 percent excess air dilution estimate is factored into the HCl levels, the standard HCl ranges would therefore be 0 to 400 ppm (0.04 percent) for dry APC devices and 0 to 560 ppm (0 to 0.056 percent) for wet collection.

There are currently no broad-based sulfur dioxide emission limitations for hazardous waste incinerators. Some states, such as New York, require that any industrial incinerator remove greater than 90 percent of all acid gases,[32] including SO_2. Many states have no such emission restriction. As a result, it is difficult to make an estimate on stack gas SO_2 concentrations, especially for dry collection devices. Without knowledge of specific applicable state regulations, a conservative estimate must assume that no SO_2 removal is required and that the pre-APC device SO_2 concentration estimate of 5000 ppm remains unchanged except for the dilution of additional excess air, resulting in a stack gas level of 4000 ppm. This concentration is roughly twice the SO_2 level found in the stack gas of a power generating facility burning coal with a sulfur content of 4 percent.[33] When wet scrubbers are employed, sulfur dioxide emissions will be removed together with HCl. Sulfur dioxide removal efficiencies of up to 40 percent have been reported at power stations, for scrubbers which were employed primarily for particulate emission control.[34] The use of alkali solutions in scrubbers can boost SO_2 removal efficiencies over 90 percent.[33] Technology, principally developed for the electrical power industry, is currently available to lower flue gas sulfur dioxide emissions to virtually any level desired.[35] For the purpose of this report, it is assumed that once a wet scrubber is to be installed for a hazardous waste incinerator, it will be designed for SO_2 removal efficiencies in excess of 80 percent. Adding the additional dilution affect of infiltrating excess air, the range of expected stack gas SO_2 levels is estimated to be from 0 to 800 ppm.

Nitrogen oxide emissions are not amenable to control by scrubbing or other post generation removal techniques.[2] Excessive NO_x emissions, if present, must be addressed at the incinerator with the installation of a reduction furnace. While the literature reports NO_x removal efficiencies of up to 25 percent can be obtained with certain scrubber designs, such removal requires NO_x levels in excess of 10,000 ppm.[33] This elevated NO_x concentration is unlikely in hazardous waste incinerator effluents, and thus this scrubber efficiency is not applicable. Consequently the estimated NO_x range at the stack for both dry and wet processes will be the 5000 ppm level assumed before the APC device diluted by an additional 20 percent excess air, or 0 to 4000 ppm.

Rotary Kiln

Once the incinerator combustion gases exit the combustion chamber, the control is dependent upon flue gas composition and not on the type of incinerator employed. As a result the stack gas quality from all incinerator designs is similar and the rationale that was presented for liquid injection incinerators is equally applicable for rotary kiln and fluidized to bed units.

The estimated stack temperature is primarily a function of the type of APC device employed. Electrostatic precipitators and fabric filters are associated with higher temperatures due to the problems of acid gas condensation previously discussed. Wet scrubbers operate at lower temperatures due to the cooling affects of water. Allowing for these factors

and a temperature loss from the control device to the stack, estimated temperature ranges are 80 to 280°C (175 to 535°F) for dry collection, and 60 to 90°C (140 to 190°F) for wet air pollution control.

The analysis presented under liquid injection incinerators for stack gas pressure is also applicable for rotary kiln effluents as the location of the prime air movement fan in the system is identical. Stack pressure will vary from 2.0 to +2.0 in. w.g., depending on where in the stack the measurement is taken.

The assumptions in which the stack gas excess air rate and the oxygen and carbon dioxide concentrations were previously based also holds true for rotary kiln incinerators. Excess air should remain relatively constant through the APC device, and then increase slightly due to potential leakage. For both wet and dry control this increase is estimated at 20 percent, bringing stack excess air estimates to between 100 and 230 percent.

The corresponding oxygen concentration for these excess air rates is also identical for both wet and dry APC control, varying from 10 to 14 percent. The carbon dioxide levels will be slightly different between dry and wet devices due to the absorbtion of CO_2 in a wet scrubber. It is estimated that incineration systems using dry APC devices will have stack gas CO_2 concentrations ranging from 3 to 8 percent, while those employing scrubbers will have a 2 to 7 percent CO_2 range.

Carbon monoxide levels are assumed to be unchanged across the APC device. The range given in Table 8 for the pre to APC location will be the same at the stack; 0 to 50 ppm.

Flue gas moisture levels will be affected as discussed earlier; for dry collection, the moisture content will remain at 3 to 10 percent. For wet collection devices, the stack gas is assumed to be saturated with moisture at the stack temperature, thereby setting the moisture content between 20 to 63.5 percent. Should the stack gas be reheated to avoid condensation of acid gases on the stack walls,[36] this moisture content may be somewhat lower.

Hydrogen chloride emissions will be limited by corrosion factors, in the case of dry APC devices, and by federal regulatory requirements, as far as wet scrubbers are concerned. Dry devices have a practical maximum HCl limit of approximately 500 ppm. Should HCl concentrations in excess of this limit be projected for a dry APC device, then dry scrubbing, waste blending or some similar control technique will be used to minimize emissions into the device. Dry scrubbing, for example, is capable of removing in excess of 99 percent of HCl and 85 percent of SO_2 from a gas stream.[37] We will assume that the 500 ppm HCl limit will be the maximum concentration that dry flue gas streams will contain at the control device inlet, and that the addition of 20 percent excess air between the fan and the stack will reduce this concentration to 400 ppm, or 0.04 percent.

As discussed earlier, federal regulations require 99 percent control for HCl. As the rotary kiln HCl emissions have been diluted by the higher excess air rates of these units, both APC device inlet and outlet HCl emissions are lower than similar liquid injection incinerator emissions. Ninety nine percent control on a maximum inlet HCl emission level of 2 percent will result in an outlet concentration of 200 ppm. If this concentration is further reduced by the 20 percent excess air infiltration estimate, stack gas HCl levels will range from 0 to 160 ppm (0 to 0.016 percent).

There is a wide range of potential stack gas SO_2 emission rates. For dry APC devices, a worst case (maximum emission) scenario would have no change in SO_2 rates across the APC device, and a slight reduction at the stack monitoring location due only to the affects of dilution air. This worst case range would therefore be 0 to 1200 ppm. Should dry scrubbing be practiced, the uncontrolled emission rate given in Table 8 could be reduced as much as 85 percent.

Wet scrubbers can be designed to remove as much SO_2 as required. If we assume that a scrubber installed for HCl control will remove at least 80 percent of the flue gas SO_2, the APC device outlet emissions will total 300 ppm. If we further assume, as before, that this level is diluted by an additional 20 percent fugitive excess air, the stack gas SO_2 range will be 0 to 240 ppm.

Finally, NO_x levels are conservatively assumed not to be affected by any form of wet or dry scrubbing. Stack gas NO_x levels will be reduced only by the additional 20 percent excess air. Stack gas NO_x concentrations for both dry and wet devices are estimated at 0 to 1600 ppm.

Fluidized-Bed

The estimated stack gas temperature and pressure for fluidized to bed units is identical to those values proposed for liquid injection and rotary kiln incinerators. Systems using dry APC devices will have stack temperatures ranging from 80 to 280°C (175 to 535°F), while those with wet devices will probably experience temperatures in the 60 to 90°C (140 to 190°F) range. Stack pressures, regardless of device, will vary from -2.0 to +2.0 inches, water gauge.

The excess air rate is again assumed to remain essentially unchanged until the fan. After this point an additional 20 percent excess air rate is assumed to account for potential leakage into the stack. Resulting stack gas excess air rate therefore ranges from 30 to 70 percent.

This increased excess air rate will translate into a stack oxygen concentration of from 5 to 9 percent for all types of systems. Carbon dioxide concentrations will vary depending on the type of air cleaner employed. Systems using dry APC devices will experience stack gas CO_2 in the 8 to 12 percent range. Wet devices, with some CO_2 absorption, will have slightly lower values, varying from 7 to 11 percent.

As with the other systems, carbon monoxide is assumed not to change across the APC device. A maximum CO concentration of 50 ppm can be anticipated in the fluidized bed stack.

The correlation between stack gas moisture levels and type of APC device utilized is the same for fluidized bed incinerators. Dry cleaning systems will see their moisture levels essentially unchanged at 5 to 25 percent. Wet systems will typically demonstrate levels in the 20 to 63.5 percent range, assuming the stack contains a saturated flue gas. Stack gas moisture contents will be lower if the gas is not completely saturated or if flue gas reheating is employed for visible plume dissipation.

The analysis technique described for the pollutants of concern was also employed to estimate fluidized bed stack gas composition. The extent of pollutant removal and dilution will remain the same, although the actual emission rates are different than the other incinerator designs.

Hydrogen chloride in dry systems is estimated to be a maximum of 400 ppm (0.04 percent). Wet scrubbers, with 99 percent minimum control will produce maximum stack levels in the 100 ppm range. Accounting for additional dilution air, this level will be approximately 80 ppm (0.008 percent).

Sulfur dioxide emissions are assumed to be unaffected by dry APC devices. The stack gas level of SO_2 is affected only by additional dilution air and will, at a maximum, reach 800 ppm. Wet systems will scrub an approximate 80 percent of the SO_2 from the flue gas. When the remaining SO_2 is further diluted by a 20 percent air leakage rate, the resulting stack gas SO_2 range is 0 to 160 ppm.

Finally, NO_x emissions are estimated to be unaffected by any type of APC control. The stack gas concentration is diluted by infiltration air to a maximum level of 1200 ppm.

SECTION 6

CONCLUSIONS

Continuous emission monitors (CEMS) that are used to measure the performance of a hazardous waste incinerator must be equipped to experience a wide range of environments. Depending on where in the total incineration system the CEM is placed, it can potentially encounter temperature extremes of up to 1700°C (3000°F), moisture levels between from 3 to 65 percent and acid gas levels that may simultaneously reach several thousand parts per million for each of several different pollutants. In addition, the CEM and its associated support apparatus must be sufficiently versatile to be adapted to the hot, confined atmosphere at the combustion zone outlet, as well as to the exposed sampling location of an exhaust stack. Obtaining representative flue gas samples from a hazardous waste incinerator presents a difficult and unique challenge that requires a thorough knowledge of the system and comprehensive planning for the wide range of conditions that may be experienced.

This report has attempted to define the limits of flue gas conditions that may be encountered in an incineration system that is combusting Appendix XIII hazardous waste constituents. This has been a difficult task given the wide number of variables that can dramatically change the flue gas composition from one facility to another and from one burn to another at the same facility. Nonetheless, estimates based on a knowledge of the waste and the equipment used for incineration and air pollution control have been made, in order to define "worst case" situations. Continuous emissions monitors that are designed to withstand these maximum flue gas conditions should be equipped to measure any combination of intermediate values.

Perhaps the greatest variable in hazardous waste incineration is the waste itself. Unlike municipal solid waste or sewage sludge, whose composition, combustion, and emission characteristics are well documented, Appendix VIII hazardous wastes are relatively unknown. While the chemical structure of all 375 Appendix VIII substances has been identified, characteristics such as auto-ignition temperatures, heats of combustion, time/temperature destruction requirements and incomplete combustion products have only recently begun to be studied in depth. Moreover, the affect that blending of various hazardous constituents has on the incinerability of any individual waste constituent is not well known. Hazardous waste is unlike municipal solid waste, specific industrial manufacturing waste, municipal sewage sludge and conventional fossil fuels in that it is not homogeneous. The 375 hazardous constituents can be blended to form an inexhaustable number

of potentially incinerable waste streams. These streams in turn can produce an unlimited combination of pollutant emission concentrations. The task of quantifying the extremes in these pollutant levels was further hampered by the general lack of well documented, published test data. The data that is available was usually associated with a one-of-a-kind research test, and these results are not necessarily representative of what might occur in the field. To ensure that the worst case pollutant emission levels were stated in this study, all judgements concerning emissions were conservative, in that they may have overstated the maximum possible emission rate. For example, estimates of 5000 ppm for NO_x and SO_x emissions and a 7 percent HCl concentration from liquid injection incinerators may have vastly over-stated the levels that will ever be seen from these units in actual test conditions. Nevertheless, using the rationale presented in the body of the report, such levels may potentially be encountered. To ensure that the CEM is adequately prepared for the absolute worst case situation, the highest potential pollutant level was used as a maximum value.

A similiar ambiguity existed for hazardous waste incinerators. Hazardous waste incineration is, itself, not new. Through mid-1981, up to 342 hazardous waste incinerators were in active service.[16] All but two of these units are employed at specific industrial sites. The technologies employed by these incinerators was, for the most part, also not new, with virtually two thirds of active hazardous waste incinerators using the common liquid injection design. The basic design and operating principles of these incinerators are well documented and have been presented in Section 3. The key variable with incinerators is, however, actual operation. From the limited test data that is available, it appears that incinerators are not always run as designed. They may be operated with higher temperatures or excess air levels than required to ensure complete waste destruction, or they may be run at less than optimum capacity, and this would change such parameters as excess air rates and oxygen and carbon dioxide concentrations. In arriving at the parameter estimates presented in Tables 7 through 9, basic assumptions on incinerator operation were assumed; that it operated at or near peak thermal and combustion efficiency, that it was well monitored, maintained and run, and that operating values were close to design values. Individual hazardous waste incinerators may be encountered, whose flue gas parameters fall outside those stated in Tables 7 through 9. However, based on currently available data, such cases are thought to be the exception and not the rule.

Section 4 presented the principal air pollution control device that may be used in conjunction with a hazardous waste incinerator. At least one APC device is required with most incinerators, but a number of installations (especially commercial incinerators), require two devices, in series with each other. The selection of any device will be based on applicable emission regulations, the type and variability of the wastes burned and the type of incinerator employed. The most commonly used devices include the venturi scrubbers and packed tower scrubbers. The former is particularly effective with high particulate loadings in the exhaust gases, and the latter is most effective in removing soluble acid gases providing the particulate loading is low. Fabric filters have temperature limitations and do nothing to gases.

ESPs are very effective for particulate removal but have a high capital cost.[16] Due to these restrictions, fabric filters and ESPs were not discussed in depth in this report. Nevertheless, if these "dry" devices are employed, the characteristics of the flue gas stream will change dramatically, so a distinction had to be made between "wet" and "dry" air pollution control. Finally, heat recovery devices are becoming an integral part of most new incineration systems,[16] so a further distinction was required to differentiate between gas streams that were cooled by heat recovery and those that used quench chambers to lower gas temperature by water cooling.

The focal point of the report is the definition of actual CEM parameters for the three monitoring zones of interest, which is reported in Section 5. The most extreme conditions for all three incinerator designs will be found in the combuston zone. Temperatures are at an extreme in this zone for all incinerators and maximum concentrations of all pollutants will be found here. This high temperature/high pollutant (especially acid gas) combination makes sampling a particularly difficult task, as the sampling probe must be shielded from the corrosive properties of the acid gases while the probe as well as the gas stream must be cooled and conditioned. Liquid injection incinerators present the greatest sampling challenge, as the range of potential temperatures, pressures and pollutant levels are the highest of all three incinerator designs. By comparison, fluidized bed incinerators have the least severe conditions, with lower temperature, air flow and pollutant emissions. Due to the difficulty of sampling the actual combustion zone of a rotary kiln, these incinerators must have combustion samples obtained downstream of the associated afterburner.

The second sampling zone is located after the flue gas cooling device but before the air pollution control. This site can be characterized by the uniform temperatures that will follow either heat recovery or water quenching, regardless of the type of incinerator used. Systems employing heat recovery will have higher temperatures at this point in order to avoid potential acid gas condensation on internal heat exchanger surfaces. Some systems may employ both heat recovery and water quenching in series. For these systems, the water quenching parameter data will apply. In addition, certain incinerator systems that employ venturi scrubbers may utilize neither form of heat recovery. Flue gas temperatures for these systems may approach 1090°C (2600°F) at this monitoring location. Such installations are thought to be atypical, and were therefore not included in setting standard temperature ranges.

The pressure variation at this second monitoring site will be the greatest of any of the locations, and will depend upon the pressure drop of the cooling device. All other CEM parameters at this location, with the exception of moisture content, will be the same as those of the combustion zone. Flue gas moisture content will depend on whether a dry or wet cooling device is used. For dry devices, there will be no change in moisture levels. For water cooling, moisture levels may represent as much as 65 percent of the total flue gas volume. Again, individual incineration facility practices will dictate exact moisture levels.

The final CEM sampling site will be located after the APC device, usually in the exhaust stack. Here, flue gas temperatures will be at their lowest level of the entire system, pressures will be within a fairly narrow range, and excess air rates will be at their greatest. The moisture level of the gas stream may be equal to or somewhat lower than the pre-APC device location. The carbon monoxide content of the gas stream will also be at the lowest level of any point in the entire system. Concentrations of acid gases can vary considerably, depending on what, if any, emission limitation must be met. The establishment of ranges for SO_2, HCl and NO_x at this final monitoring point was the most difficult part of this assignment, as regulations in this area are still under development by many states. As a result stack emissions, particularly for SO_2 and NO_x, can run the gamut from essentially uncontrolled to control down to one-tenth or one one-hundredth of uncontrolled levels. Consequently, the estimates presented in Table 9 for acid gas levels could be as much as one or two orders of magnitude higher than what might be observed in the field. The range of possible variables that play a part in estimating emission rates as well as the desire to define absolute worst case emission rates precludes defining the range of emission rates any tighter.

In summary, this report has attempted to define ranges of values for the commonly encountered continuous emission monitor parameters. Due to the number of potential wastes, the equipment and operating variables that affect monitoring parameter ranges, and the general lack of comprehensive emission test data, this effort has had to principally rely on engineering estimates to define flue gas composition during incineration of Appendix VIII hazardous waste constituents. As more experience is gained in this field, these estimates can be further refined to reflect actual operating conditions.

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